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Summary of Final Report on

DESIGN STUDIES OF VERY LARGE SOLID FUEL ROCKETS

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GRAND CENTRAL ROCKET CO.
REDLANDS CALIFORNIA

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GCR Report No. S-0041-61

SUMMARY OF FINAL REPORT ON DESIGN STUDIES OF VERY LARGE SOLID FUEL ROCKETS

Letter Contract NAS5-672 (MPO 537)
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

9 April 1961

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Redlands, California

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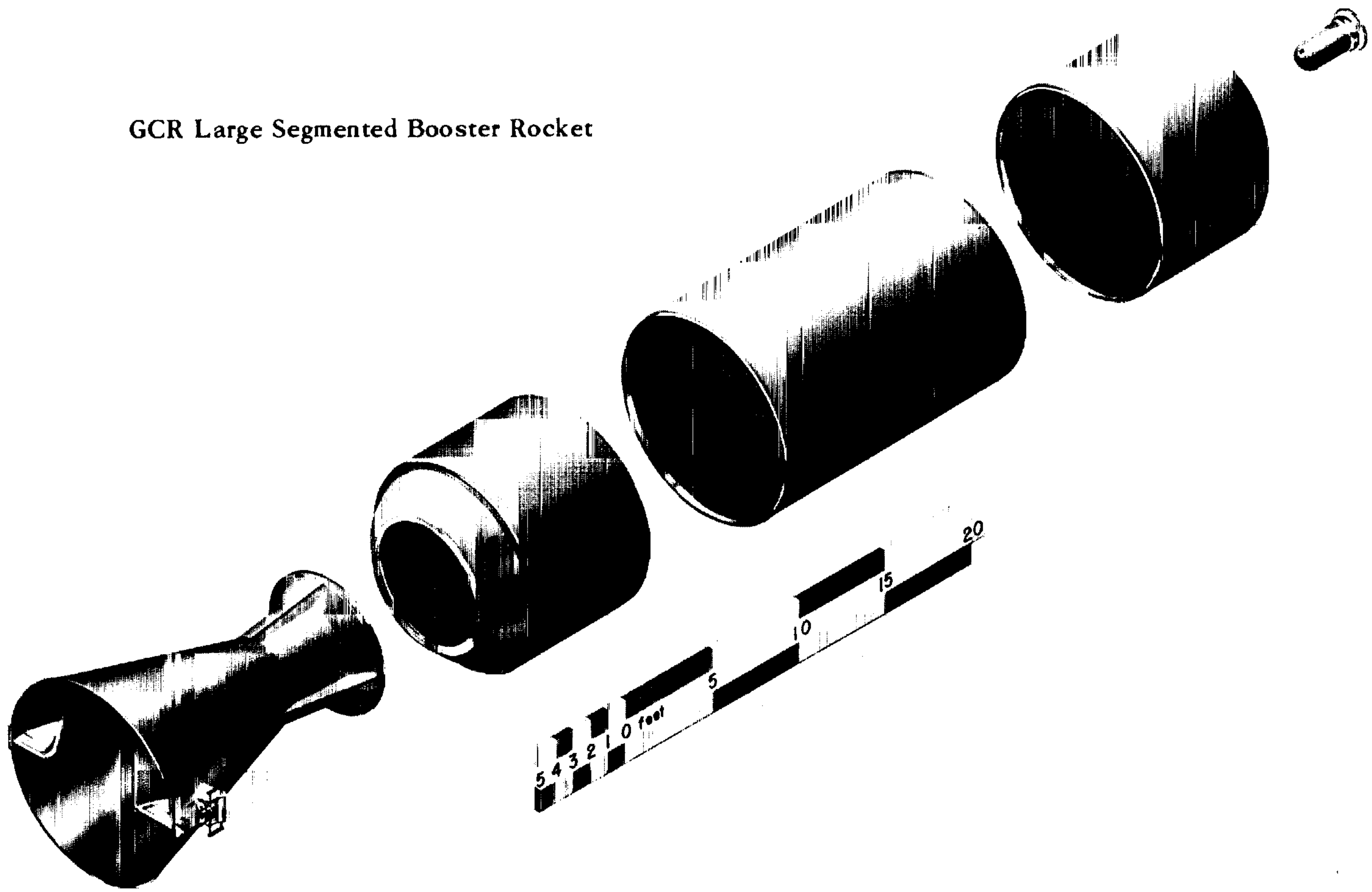
CONTENTS

TABLES

FIGURES

FIGURES (Continued)

GCR Large Segmented Booster Rocket



I. SUMMARY

Under sponsorship of the National Aeronautics and Space Administration, Grand Central Rocket Co. has performed a detailed study to determine an optimum solid-fueled rocket configuration, within present technology, to boost ultra-large satellite and space payloads.

The Grand Central Rocket Booster Motor design utilizes "building block" segments of circular configuration readily capable of being stacked and clustered. The design features:

SIMPLICITY

RELIABILITY

ADAPTABILITY

LOW COST

Reliability is inherent in simplicity, and reliability and adaptability are the best guarantees of low cost in a launch vehicle program. These factors were actual design criteria.

The design approach proposed by Grand Central Rocket Co. recommends the use of segmented motor parts to be transported separately to the test site and assembled prior to launch. This approach will provide:

(1) Easy handling of boosters with conventional manufacturing facilities and transportation equipment.

(2) Exceptional thrust versatility for a wide variety of booster applications.

Clusters of three or more segmented motors can be employed for very large orbital payloads or space missions. Figure 1 depicts such a cluster of solid rocket boosters in a Saturn-type configuration.

The principal points of comparison between large liquid propellant boosters and large solid propellant boosters may be summarized (Table I) by relating the Saturn Booster (cluster of eight engines) to a cluster of three 3-segment, 10-foot diameter solid propellant motors.

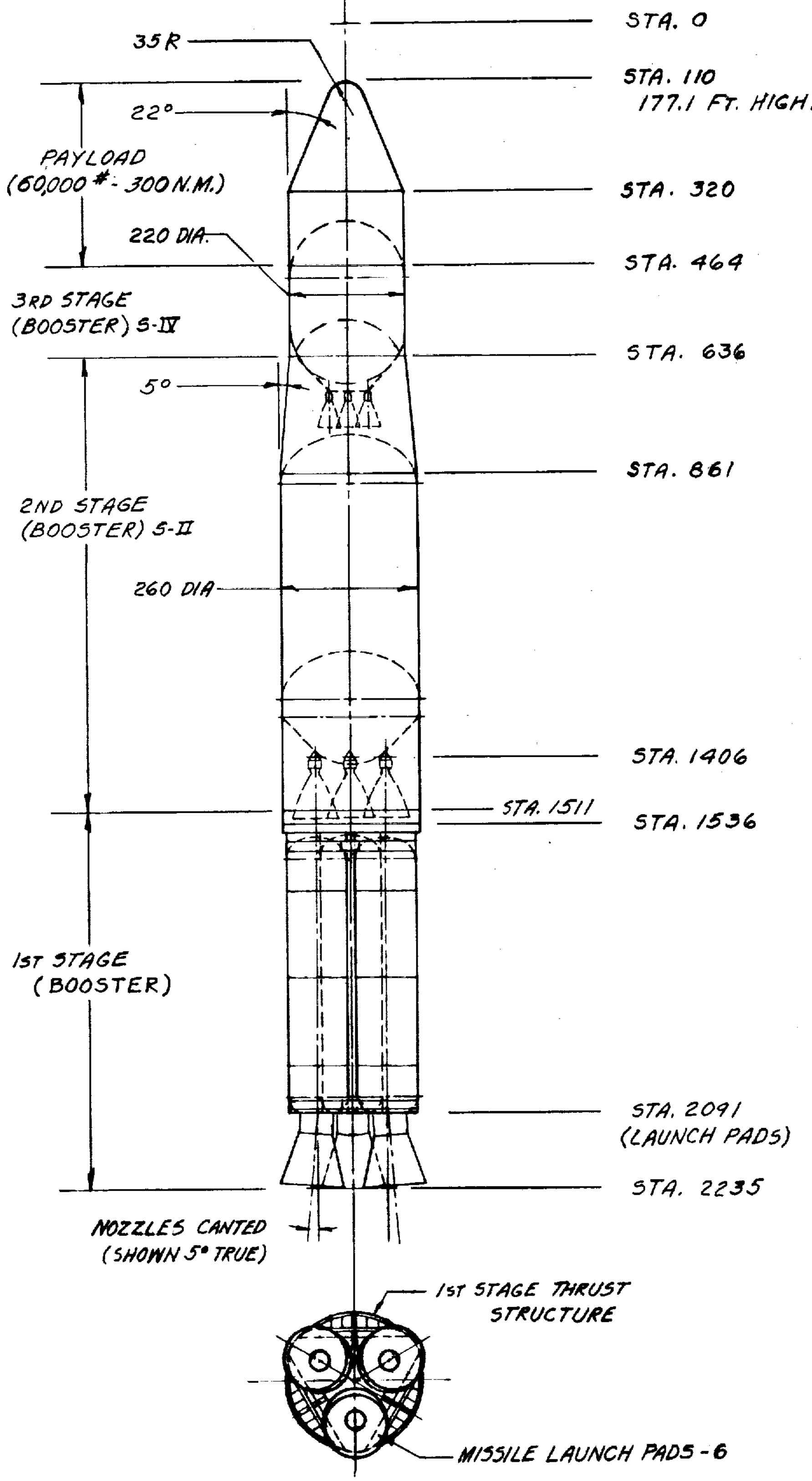


Figure 1 Saturn-Type Configuration, One-Million Pound Gross Weight Category, Vehicle No. 1

TABLE I
COMPARISON OF LARGE BOOSTERS: LIQUID AND SOLID

	Liquid Cluster of Eight Engines Saturn S-1	Solid Cluster of Three 3-Segment Motors
Development Cost in millions of dollars, including delivery of 10 flight boosters.	487	75
Development Time in years	6	3
Payload in pounds (using H_2-O_2 upper stages in orbital missions)	48,000	60,000
Immediate Growth Potential in percent of total impulse	limited	100
Payload Cost in dollars per pound in 300-mile orbit for 100 flights	731	352

For all large vehicle missions, GCR's proposed design utilizes only three basic motor building blocks plus the nozzle and thrust vectoring system. This simplicity in concept accounts for the low development cost and rapid development time and insures high reliability.

The 3-segment motor has a thrust capability of 1.33 million pounds for 45 seconds duration. When three of these motors are clustered, as would be required in Saturn-type applications, a total thrust of 4.0 million pounds is available for the same burning time. Moreover, a further thrust growth potential is available by simply adding up to three more identical segments to each of the above-mentioned 3-segment motors. This feature, which can increase thrust by a factor of two, yields a booster stage adaptability to varied mission requirements that is unequalled by "one piece" solid rockets or liquid-fuel rocket boosters.

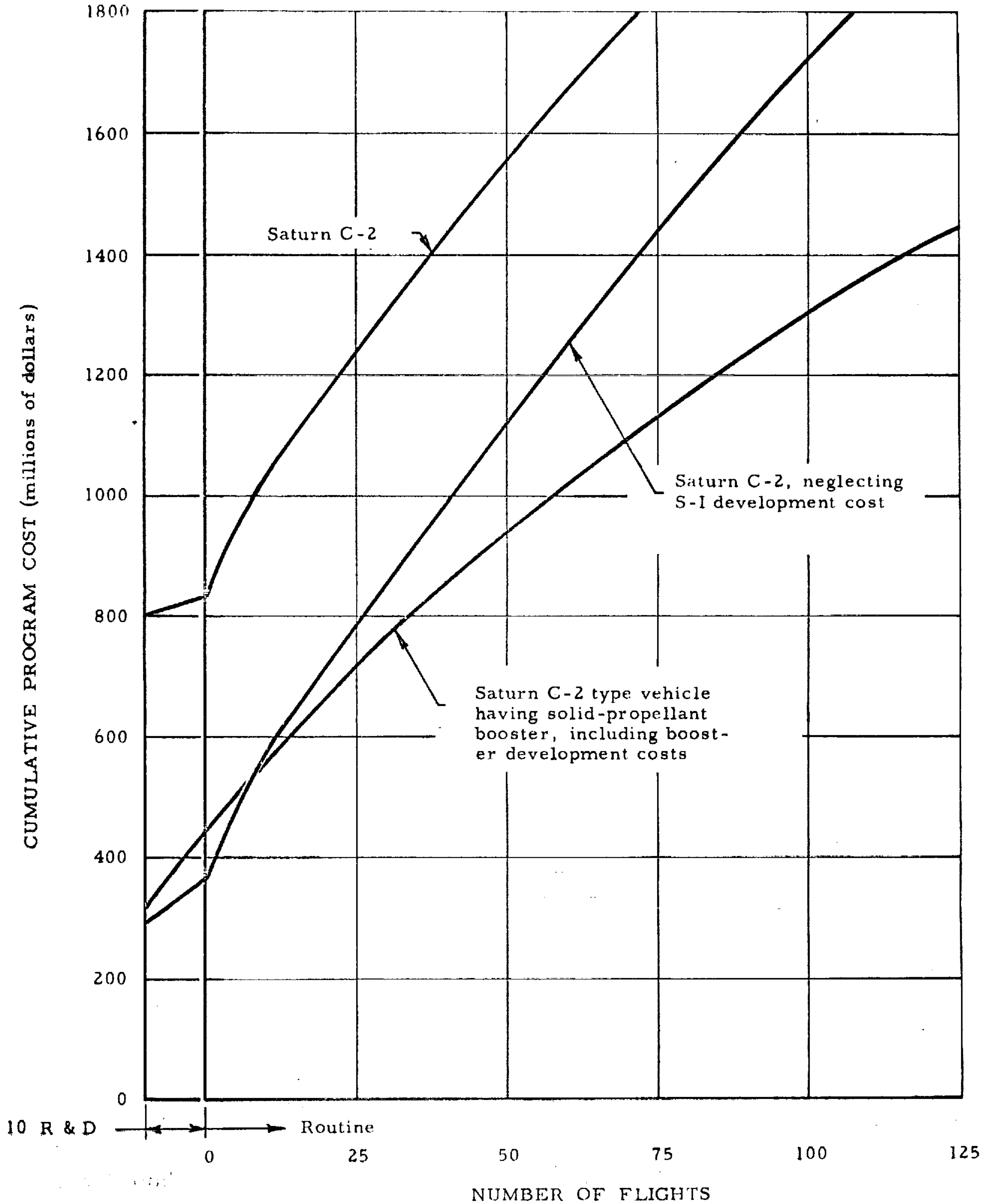


Figure 2 Total Launch Program Costs Comparison: Liquid-Boosted and Solid-Boosted Saturn C-2

The cost studies clearly show the cost advantage of a solid propellant booster over an equivalent liquid propellant booster. Accumulative booster costs in millions of dollars are shown for the two systems below:

	Saturn S-I	Clustered Solid Motors
R and D, including 10 delivery	487	75
Accumulative R and D and production for 10 flights	582	100
Accumulative R and D and production for 100 flights	1169	260

However, since the Saturn S-I development has been virtually entirely funded or committed, a comparison between the liquid booster and the solid booster was made neglecting Saturn S-I R and D costs. The summary curves, shown in Figure 2 on the page opposite, include all solid propellant booster development costs.

The study results show that through development and use of large solid propellant boosters, major cost savings to the United States are possible.

II. INTRODUCTION

This report summarizes work performed by Grand Central Rocket Co. under NASA Contract No. NAS5-672, dated 1 September 1960. The work consisted of detailed studies of the problems involved and the possible advantages to be gained in utilizing very large solid-fuel rockets as first stages in future space vehicles. Vehicles of the gross weight class of 1,000,000 pounds and 10,000,000 pounds, each utilizing a solid fuel first stage and H_2-O_2 upper stages, were investigated. The initial contract required the study of the 1,000,000-pound gross weight vehicle only but, as the program progressed, GCR included, at no additional cost, the study of the larger vehicle capable of accelerating a 130,000-pound payload to escape velocity. In each study, a large majority of the work was applied to the study of the first stage. The basic design philosophy was to develop a solid fuel booster that utilized proven design concepts and existing manufacturing technology and that emphasized simplicity, reliability, adaptability and low cost. Total vehicle cost per pound of payload was an important design consideration.

Specifically, a large segmented solid propellant motor design was prepared, including the motor case, propellant system with liner and insulation, the nozzle and thrust vector control system, the ignition system, and the self-destruct system. Clustering and interstage structures and launch facilities were also designed in preliminary form.

Maximum advantage was taken of a related program that Grand Central Rocket is conducting for the Air Force. For example, detailed and well-tested designs of segment joints were available and directly applicable to the NASA work. The Air Force effort will culminate in the manufacture and hydrostatic test of full-scale (120-inch diameter) motor cases and in the manufacture, propellant loading, and test-firing of subscale (36-inch diameter) motors. There has been very close coordination between the NASA and the AF large booster efforts at GCR, with no duplication of effort and a maximum efficiency in the conduct of both programs within their respective work statements.

The motor design of this study was chosen after careful consideration of the fabrication, testing, transportation, handling and launching aspects involved. A comprehensive development program is presented as a part of this report. A detailed cost study for the proposed development program, including facilities costs, is included.

Under subcontract to Grand Central Rocket Co., Lockheed Missile Systems Division, Sunnyvale, California, performed the launching, missile structures, and trajectory studies for the program. Both orbital and escape missions were considered.

Technical guideline for this study, including performance and cost information for the Saturn missile, was provided by NASA's Marshall Space Flight Center (MSFC), the agency designated by NASA headquarters in Washington, D.C., to coordinate the technical effort on this program.

III. GENERAL

Grand Central Rocket Co. has performed a thorough study to determine the optimum solid propellant rocket motor configuration within present technology which can be used to boost large satellite and space payloads. The design is predicated on utilizing H_2-O_2 upper stages which are presently available or are under development. As discussed in the Introduction, boosters for two basic categories of launch vehicles were investigated. The first is a 1-million pound gross weight vehicle of approximately Saturn C-2 payload capability, and the second has an escape mission payload capability of approximately 130,000 pounds, which is that required for the NASA's manned lunar program. The latter vehicle has a launch weight of approximately 10 million pounds. For simplicity, these launch vehicles are referred to as "Vehicle No. 1" and "Vehicle No. 2". Both vehicle designs utilize the same basic feature: clusters of segmented solid propellant boosters.

The basic booster motor has an inside diameter of 116 inches and uses untapered segments of 14 feet in length. The 3-segment motor has two such segments plus elongated end domes, or "half-segments". (The combined propellant weight in the forward- and aft-end sections approximates the propellant weight in a single cylindrical segment.) A 5-segment motor thus has four identical segments plus the end domes. Figure 3 shows design details of a segmented booster.

Following an analysis of many possible motor sizes and configurations for a booster of a 1 million-pound gross weight vehicle, the 116-inch diameter was selected for these reasons:

(1) A cluster of three 3-segment 116-inch diameter motors will not only provide a payload capacity 25 percent greater than the Saturn S-I, but it will provide an immediate post-Saturn growth potential simply by permitting the addition of more identical segments to the motors. This fact gives the rocket a greater useful "life" than smaller sizes.

(2) The use of a cluster of three motors for a Saturn-type application will provide NASA with early information on feasibility of the large motor clustering concept, envisioned as being required in future space launch vehicle boosters.

(3) The 116-inch diameter segments are the heaviest units (90,000 lb) permitting highway transportability on a routine basis, providing many obvious advantages in logistics flexibility.

(4) The cluster of three 116-inch diameter motors has approximately the same diameter as the 21-foot wide S-II hydrogen-oxygen second stage, obviating many problems of interstage connection.

In view of the above facts, it is believed that the 116-inch diameter size is a useful, necessary, and logical technical stepping-stone toward the potential development of "super"-size solid propellant rockets. The technology of 10-foot diameter rockets is the same as that for 12- or 14-foot diameter motors. This fact, coupled with the rocket's mission capability, means that no appreciable amount of time would be lose in the evolution of NOVA-class vehicles by development of a 10-foot diameter booster.

The motor design incorporates a case-bonded propellant grain having a simple circular internal perforation. The ends of the segment grains are uninhibited, permitting these surfaces to burn throughout the full motor duration. By this design, the maximum of motor performance reliability and reproducibility is attained.

The segmented motor case was chosen rather than the single large motor case because of the following advantages:

(1) Improved reliability permitted by the use of a simple circular grain shape and low length-to-diameter ratio of the individual grains. This grain configuration minimizes grain stress concentrations and assures the highest possible propellant integrity under handling and flight loads.

(2) Flexibility of application to various required missions.

(3) Maximum freedom from the high cost of any potential motor case or grain defect.

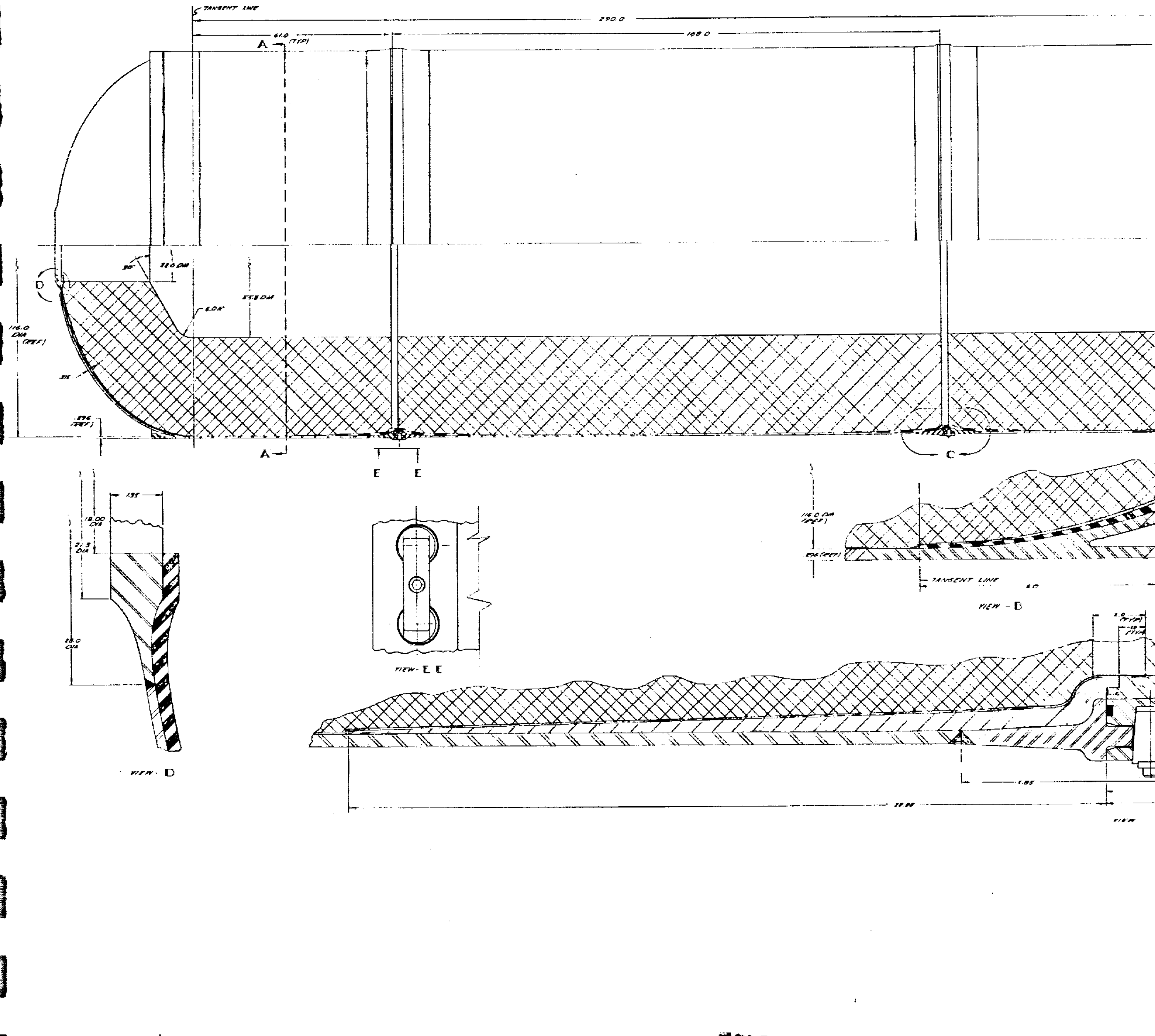
(4) Ease of motor case manufacturing, ease of handling during processing, and ease of transportation. Ease in these operations is directly related to lower cost.

(5) Ease and adequacy of inspection during and following motor manufacture.

(6) Elimination of requirement for launch-site casting operations, which would have inherently greater costs and poorer quality control than processing at the manufacturer's facility.

(7) Elimination of requirement for handling of the fully-loaded booster and associated massive handling equipment. For example, existing Saturn cranes could not possibly emplace a single-case non-segmented solid booster. The alternate approach of motor processing on the launch pad would result in prohibitively high time of launch pad occupancy.

(8) Faster and less expensive development since valid preliminary testing can be accomplished on shorter, one- or two-segment full diameter motors. Also, segmented motors, because of the relatively small size and weight of the individual segments, can be manufactured with only moderate expansion of existing facilities.



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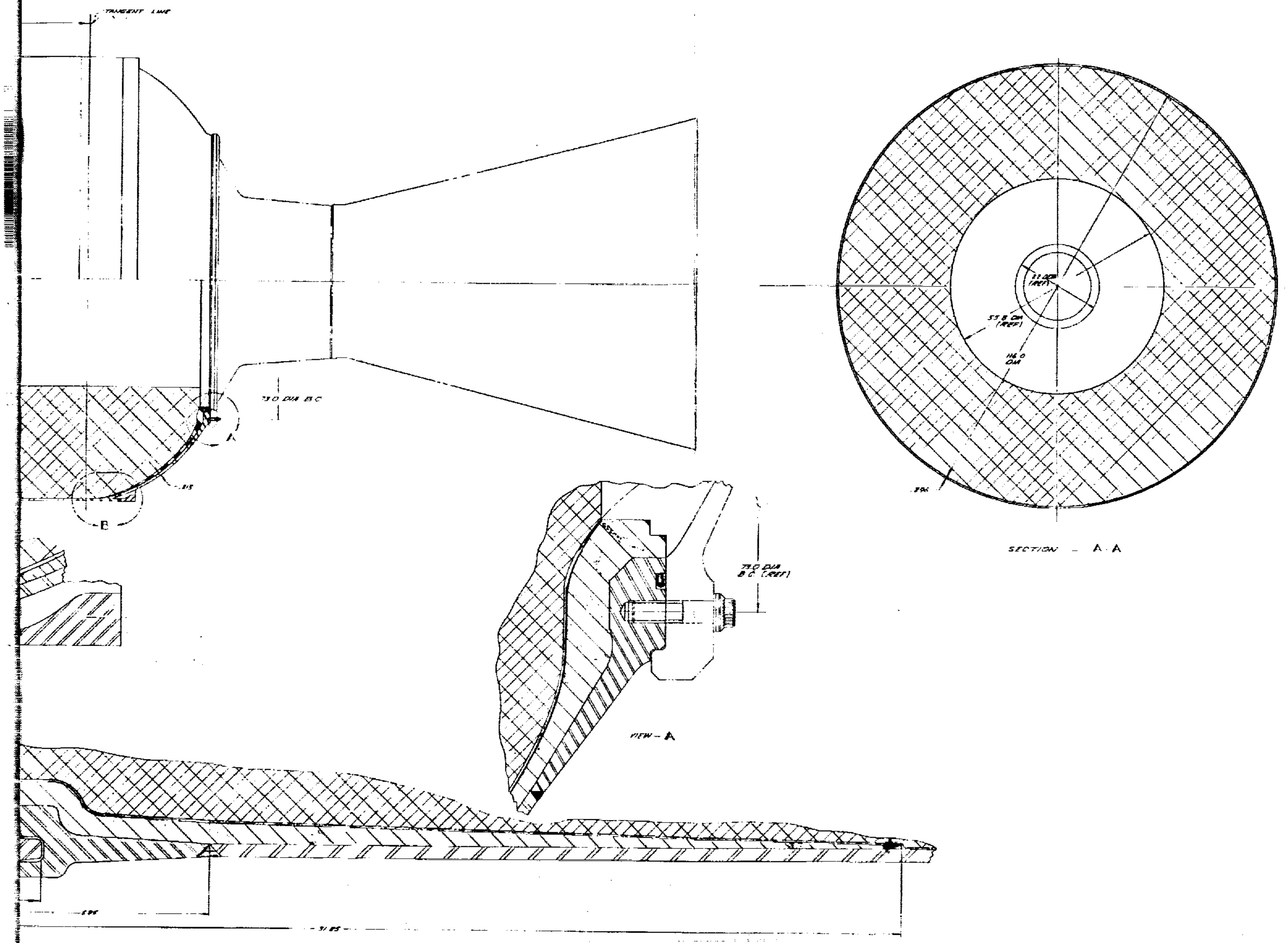

Figure 3 Design Details of a 2-Segment Booster

The performance curve of the proposed motor was designed by establishing the optimum length-to-diameter ratio of the segments. (For reasons of missile performance, a somewhat regressive thrust-time performance is desired.) This ideal shape of performance curve is maintained irrespective of the number of segments used.

Table II summarizes the propellant weight, thrust and pressure levels, and impulse values for individual 3- and 5-segment motors. These motors are used in the 1- and 10-million pound class vehicles, respectively. Table III summarizes the motor arrangement and payload capabilities of Vehicle No. 1 and Vehicle No. 2. Figure 4 shows a sketch of Vehicle No. 2.

It is strongly held that the use of simple, constant diameter motor sections, rather than tapered parts, will result in substantial improvements in motor reliability, costs, flight mission performance, and in the essence of the "building block" principle--interchangeability.

The use of a tapered internal port is not necessary to reduce "erosive" burning in efficiently designed motors of the length-to-diameter ratios desirable for space-booster applications. Figure 5 shows that even a 10-foot diameter rocket would have a growth potential to as high as 3 million pounds of thrust without problems of low port-to-throat ratio. (Early Scout booster motors had an initial port-to-throat ratio of 1.11). A constant diameter motor is believed by GCR to be more useful, more reliable, and less expensive than tapered motors because:

(1) Since tapered motor cases require all segments to be of different size, far greater costs are incurred in fabrication. For example, many sizes of joint forgings, head dies, and machining fixtures are required to manufacture various size motors.

(2) A constant diameter motor contains a greater amount of propellant than a tapered motor of the same length and maximum diameter. Consequently, the constant diameter motor reduces the number of motors required in a given length booster cluster and thereby increases the over-all reliability of the launch vehicle.

(3) For a given propellant grain web thickness, a tapered design requires an increase in web fraction toward the nose end with an inherently greater tendency to form grain cracks under processing, storage, transportation, and operational conditions.

(4) In a tapered design, since the larger diameter segments become commensurately shorter in length in buildup of very large boosters, the number of sections and joints required becomes excessive, with necessarily degraded reliability.

TABLE II

CHARACTERISTICS OF 3- AND 5-SEGMENT MOTORS

	Propellant Weight (lb)	Burning Time (sec)	Average Chamber Pressure (psia)	Average Thrust (lbf)	Total Impulse (lbf-sec)	Throat Area ($in.^2$)
3-Segment Motor	250,535	45	700	1,300,000	60,000,000	1260
5-Segment Motor	415,577	55	800	1,800,000	100,000,000	1500

TABLE III

STAGES AND PAYLOADS

ONE AND TEN MILLION-POUND CLASS VEHICLES

	Vehicle No. 1 1,000,000 lb	Vehicle No. 2 10,000,000 lb
Stage 1	Cluster of 3 solid propellant 3-segment motors	Cluster of 16 solid propellant 5-segment motors
Stage 2	S-II	Cluster of 4 solid propellant 5-segment motors
Stage 3	S-IV	Cluster of 6 J-2 engines*
Stage 4 (for escape missions)	S-V	Cluster of 2 J-2 engines
Payload (lb):		
Orbital	60,000	
Escape		130,000

*The J-2 is a 200,000-pound thrust liquid hydrogen-liquid oxygen engine currently under development. The Stage 3 engine will have twice the propellant capacity of the Satum S-II.

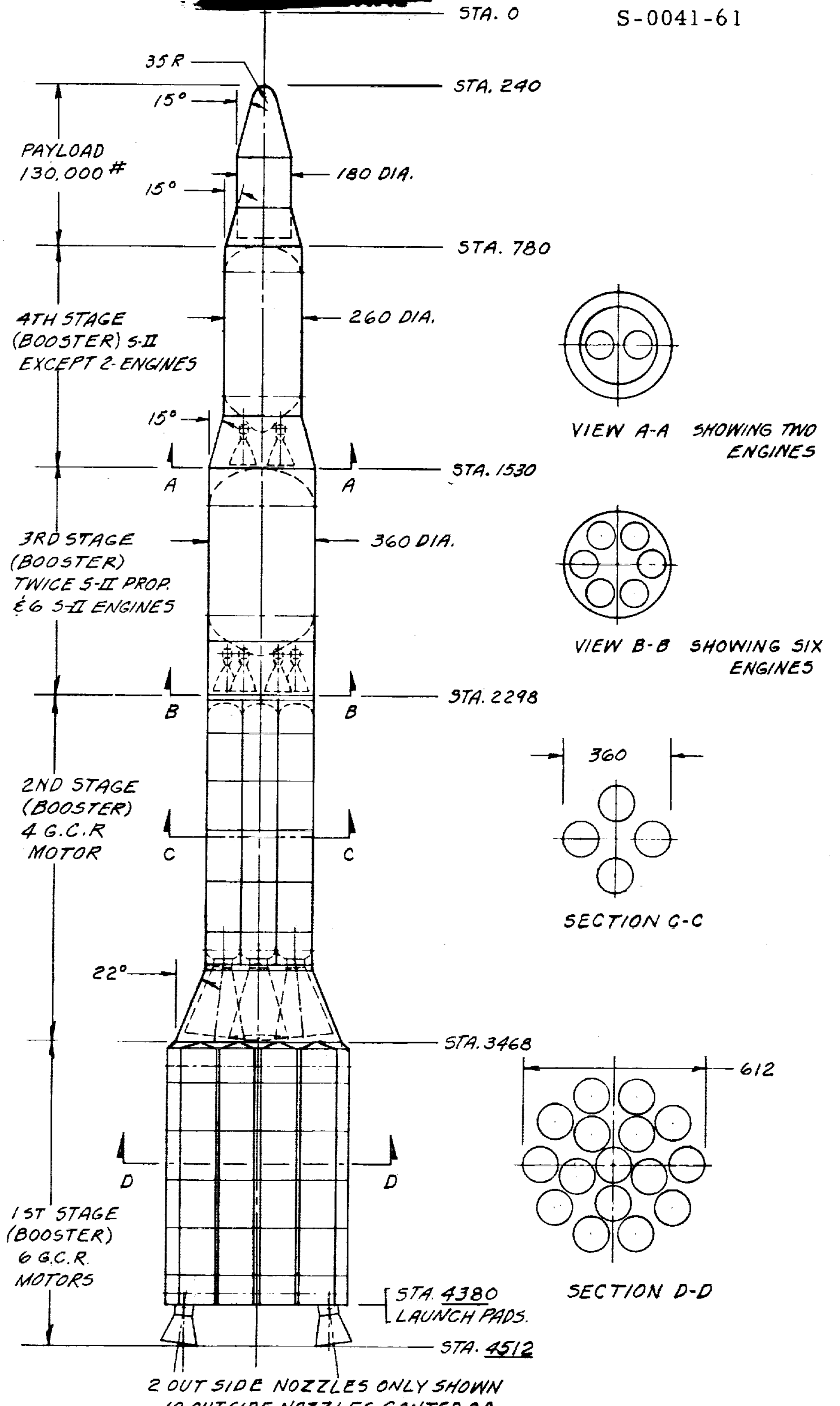

Figure 4 Vehicle No. 2, Ten Million-Pound Gross Weight Category

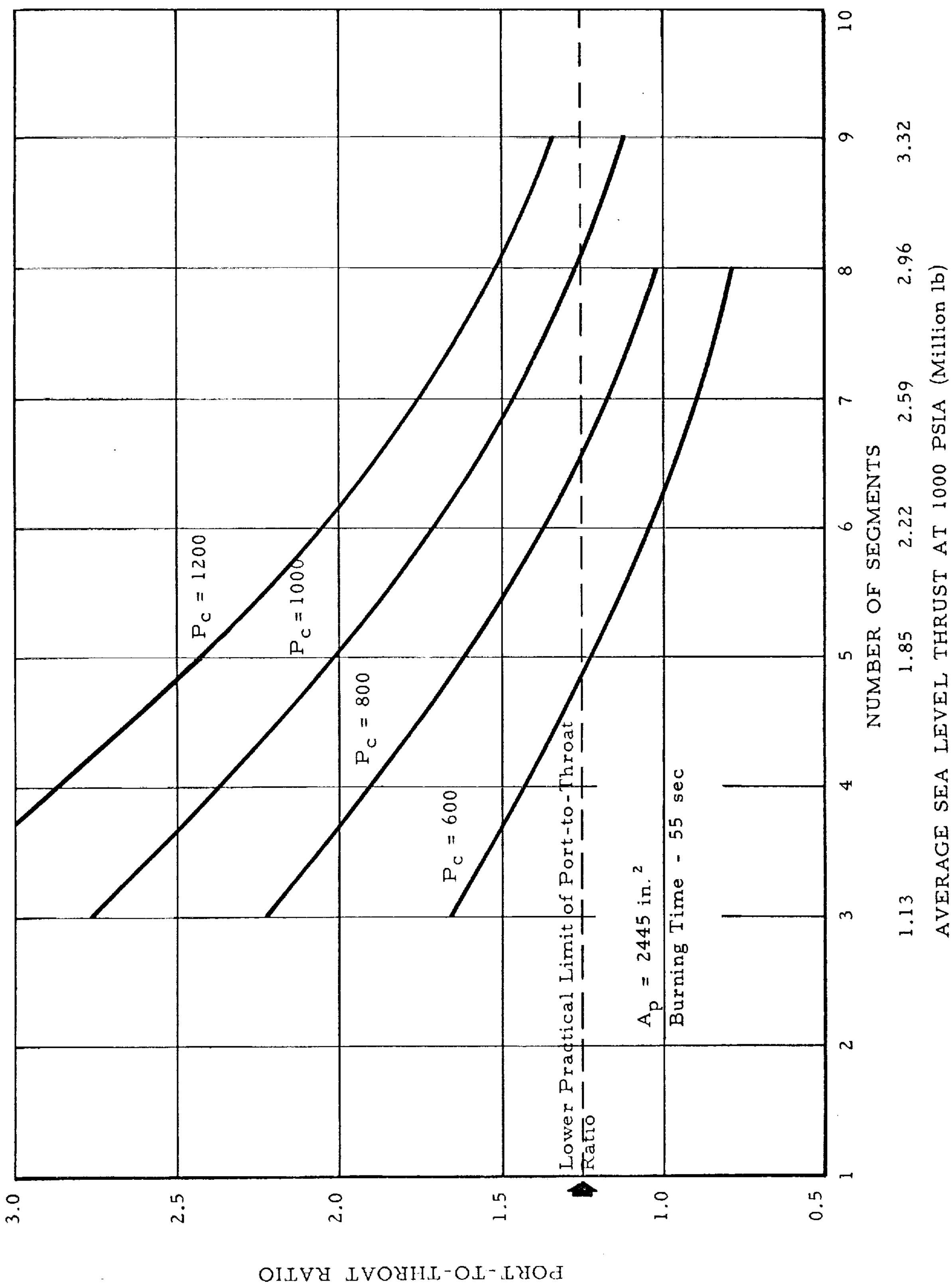

Figure 5 Variation of Port-to-Throat Ratio with Number of Motor Segments for Several Chamber Pressures

The cost bases in the solid propellant booster study have been carefully conceived, and the figures shown in Tables IV and V represent a conservative analysis based on firm cost bids from major suppliers. They include costs of parts, raw materials, labor, facilities and equipment, personnel training, motor rejection rates, parts transportation to and motor spares at the launch site, and realistic contingencies, overhead rates, and fees. Costs of detailed design and static-testing of the interstage and clustering structures and costs of systems engineering attributable to the booster stage are included in the $75 million figure for research and development. A complete breakdown of the costs is given in the detailed technical report. The cost discussion shows all assumptions made, including projected launch rates, launch pad occupancy, range services costs, and launch operations.

Tables IV and V summarize the costs for research and development, production, and routine launchings of a solid rocket boosted Saturn-class orbital mission vehicle. The costs are compared with those of the Saturn C-2 as supplied to GCR by the MSFC. The comparison assumes the use of identical H_2-O_2 fueled upper stages. The tables also assume equal costs for launch operations, GSE and facilities at the launch site, range services costs, and equal mission reliabilities.

The development schedule for the large solid boosters is shown in the Master Phasing Schedule, Figure 6. Procurement schedules of all major motor components and a line-of-balance program for the first development test-firing are shown in the detailed technical report.

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TABLE IV

COST SUMMARY

	Costs in millions of dollars: R and D	10 R and D Flight Tests	Routine Flights	Total Accum Costs	Pounds in Orbit (Million) (Liquid Reliability)*	Total Dollars per Pound Payload in Orbit	Improvement Factor Over Liquid C-2
	778	152			48,000 lb Payload		Payload per Dollar
All Liquid Saturn C-2		10 Flights	205	1135	0.182	6236	--
		100 Flights	1350	2280	3.12	731	--
	341	152			60,000 lb Payload		
C-2 with Solid Booster (3-Cluster - 3-Segment)		10 Flights	136	654	0.228	2868	2.2
		100 Flights	855	1373	3.90	352	2.1
	357	152			76,000 lb Payload		
C-2 with Solid Booster (3-Cluster - 5-Segment)		10 Flights	145	686	0.289	2374	2.6
		100 Flights	926	1467	4.94	297	2.5

*For 10 Flights: Payload x 10 x .38 (Liq. Rel.)
For 100 Flights: Payload x 100 x .65 (Liq. Rel.)

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TABLE V

COMPARISON OF COSTS OF LIQUID-PROPELLANT VERSUS SOLID-PROPELLANT BOOSTED VEHICLES USING HYDROGEN-OXYGEN UPPER STAGES, ORBITAL MISSION

	R and D				10 Flight Tests (No Useful Payloads)				Routine Flights (Useful Payloads)				
	Engineering and Test (10 ea)	Facilities and Equipment	Mfg. and Delivery (30 Del)	Sub-Total	Launch Operations	GSE and Facilities	Range Services	Sub-Total	Mfg. and Delivery	Launch Operations	GSE and Facilities	Range Services	Sub-Total
All Liquid Saturn C-2 (S-I, S-II, S-IV)		778		778	60	80	12	152					
10 Flights									159	37	0	9	205
100 Flights									1143	163	0	44	1350
C-2 with Solid Booster (3 Cluster-3-Segment)	19.0	291 11.1	44.8	291 74.9	60	80	12	152	Upper Stages Solid Booster				
10 Flights									64 25.6	37	0	9	136
100 Flights									463 185	163	0	44	855
C-2 with Solid Booster (3-Cluster-5-Segment)	25.4	291 11.1	61.4	291 97.9	60	80	12	152	Upper Stages Solid Booster				
10 Flights									64 35.4	37	0	9	145
100 Flights									463 256	163	0	44	926

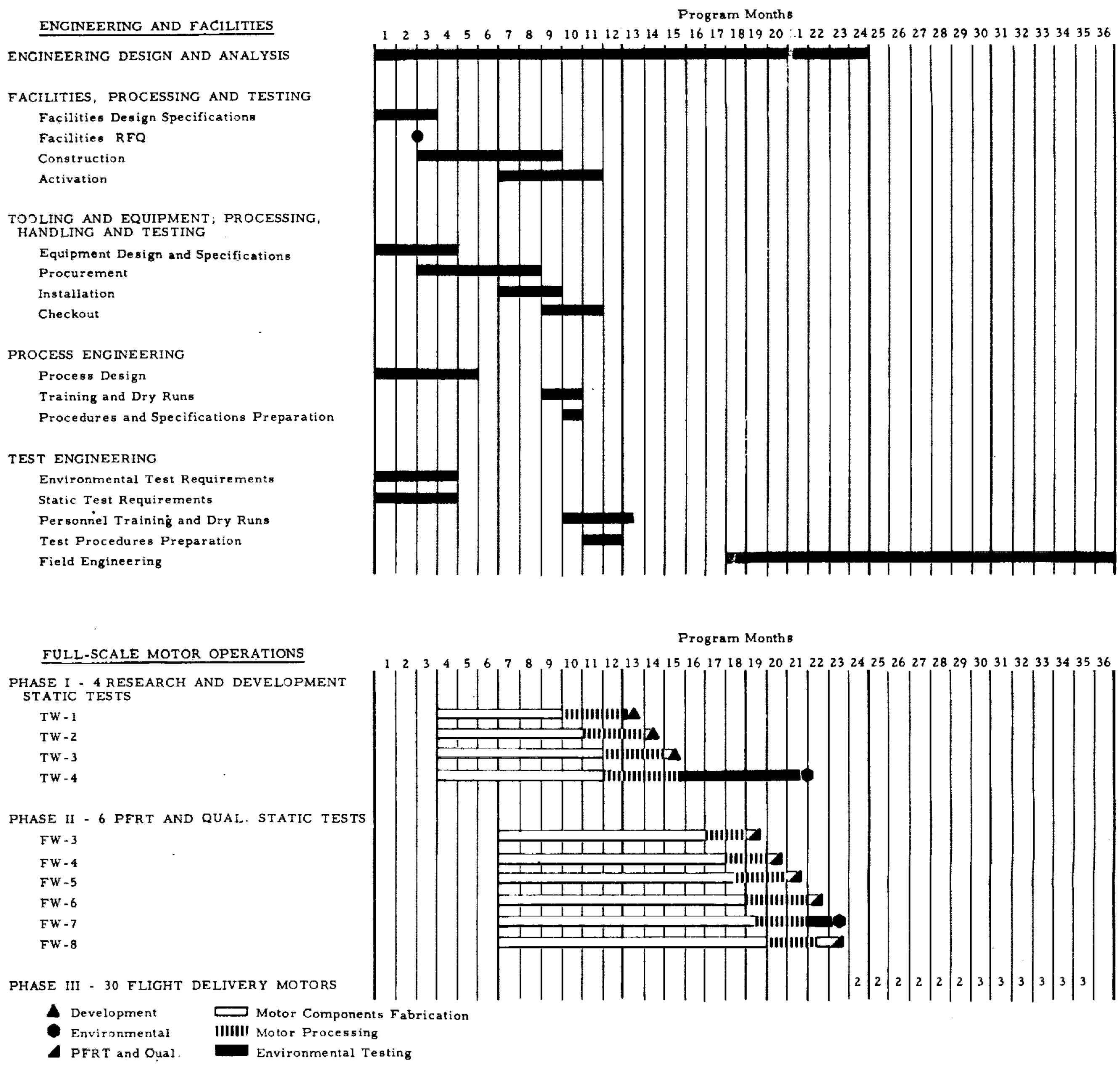
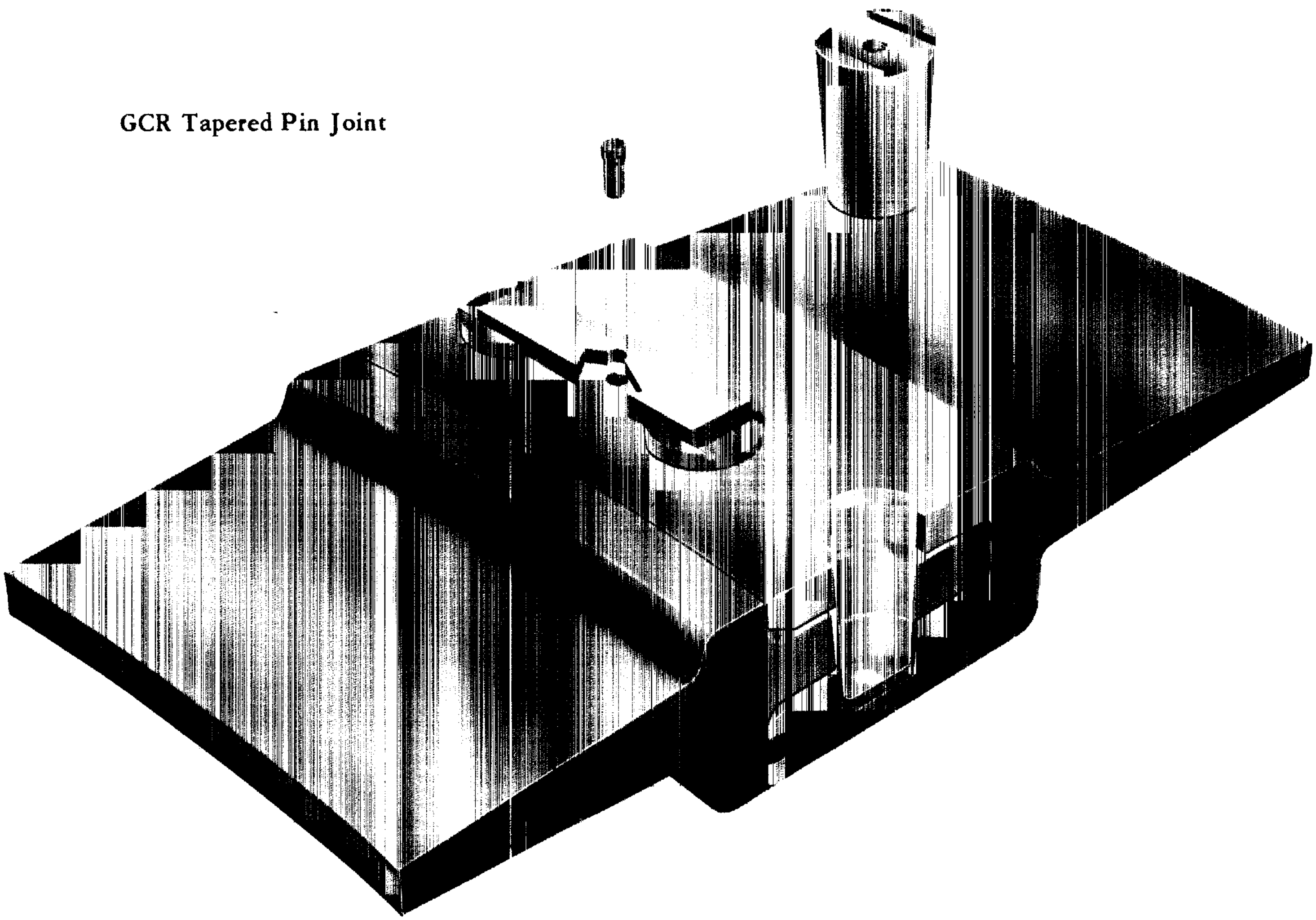


Figure 6 NASA Booster Master Phasing Schedule

GCR Tapered Pin Joint



IV. TECHNICAL SUMMARY

A. Motor Case Design

GCR conducted extensive analysis of segmented large solid booster motors, including a comprehensive material and manufacturing capabilities survey. The study included analysis of structural adequacy, fabrication and assembly considerations, weight, cost, and probable reliability of 19 different joint design concepts. This effort has resulted in the selection of an optimum overall case and joint design for large motors.

The motor design, shown in Figure 3, page 9 , incorporates the GCR tapered pin joint. This joint concept provides a combination of features not found in any other known design. Certain of these advantages are as follows:

(1) With merely a press seating of the tapered pin, full positioning of the segment joint is maintained, precluding any possibility of a "loose" connection and preventing dynamic loading of the joint upon motor pressurization.

(2) Every pin carries a full and equal shear load.

(3) A liberal and easily obtained radial tolerance is permitted in drilling the pin holes which does not require match drilling or repeated borings. This feature permits segments to be interchangeable, with obvious logistic advantages.

(4) Of all reasonable joint designs considered, this design was the lightest in weight.

(5) Due to manufacturing ease, fabrication costs are low. Conventional manufacturing techniques and equipment can maintain the required tolerances.

(6) The O-ring seals in longitudinal compression, eliminating the need for strict case roundness tolerances and precluding the possibility of cutting the O-ring during motor assembly.

The pins are held in place by bolted retaining tabs, two pins per tab. This tab serves no structural function but merely keeps the pins from falling out during motor assembly. Several other methods of pin restraint were investigated and found to be almost equally satisfactory.

The chamber design is conventional and conservative. Design factors of safety are substantially higher than those applied to the large ballistic missiles.

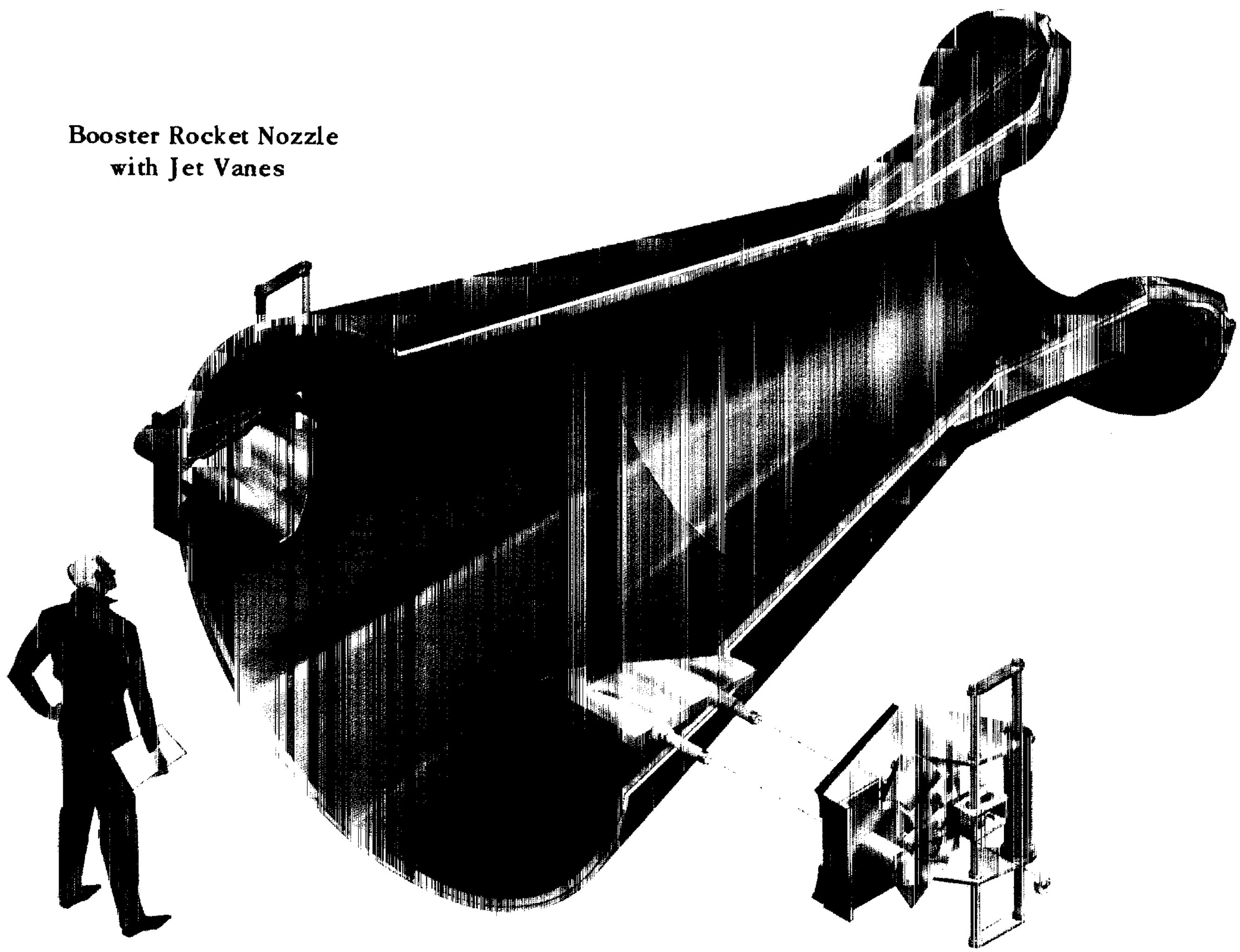
The simplicity of the proposed design--untapered sections, low tolerance requirements, and conventional and reliable roll and weld construction are design criteria which will amount to greater cost savings and more reliable performance than any other design concept. Table III shows a weight summary of motors having various numbers of segments.

TABLE VI

NASA BOOSTER WEIGHT SUMMARY

(Pounds)

Component	1-Segment	2-Segment	3-Segment	4-Segment	5-Segment
Pressure Vessel					
Forward Head	3,375	3,375	3,375	3,375	3,375
Forward Skirt	345	345	345	345	345
Closure Bolts	50	50	50	50	50
Segment	-	5,624	11,248	16,872	22,496
Segment Pins	39	78	117	156	195
Aft Head	3,365	3,365	3,365	3,365	3,365
Aft Skirt	345	345	345	345	345
	7,519	13,182	18,845	24,508	30,171
Igniter, Incl. S/A	75	100	100	120	120
Nozzle	1,840	3,170	4,490	5,810	7,140
Attitude Control System	1,780	1,900	2,020	2,140	2,260
	3,695	5,170	6,610	8,070	9,520
Insulation and Liner					
Forward Head	684	684	684	684	684
Segment	-	675	1,350	2,025	2,700
Aft Head	658	658	658	658	658
	1,342	2,017	2,692	3,367	4,042
Clustering Interconnect (per motor)	2,500	2,750	3,000	3,250	3,500
Destruct	5	5	5	5	5
Total Inert	15,061	23,124	31,152	39,200	47,238
Propellant					
Forward Head	44,501	44,501	44,501	44,501	44,501
Segment	-	82,521	165,042	247,563	330,084
Aft Head	40,992	40,992	40,992	40,992	40,992
Total Propellant	85,493	168,014	250,535	333,056	415,577
Stage Weight	100,554	191,138	281,687	372,256	462,815
Propellant Mass Fraction	0.850	0.879	0.889	0.895	0.898



Booster Rocket Nozzle
with Jet Vanes

B. Nozzle and Thrust Vector Control Design

In accordance with the Statement of Work, the principal technical effort of the program was concerned with analysis, selection and design of the nozzle and thrust vector control system. Again, simplicity and highest proven reliability were the principal design criteria. The detailed study shows that fully immersed jet vanes, possibly in conjunction with aerodynamics fins, offered the highest proven reliability of any systems studied.

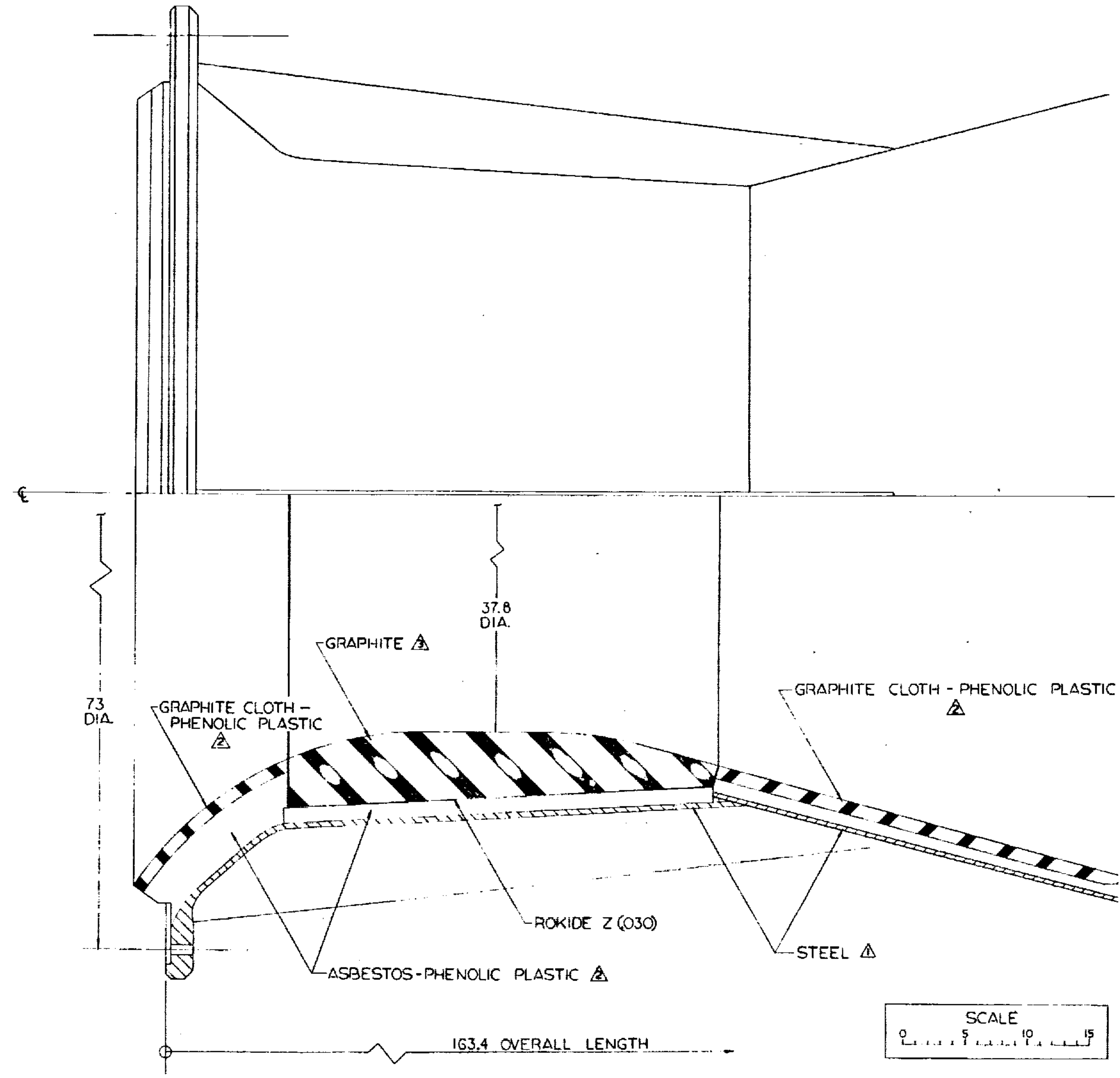
The use and size of the aerodynamic fins required is partially dependent on the particular upper stage configuration. Second in order of preference was injection of a fluid in the nozzle exit section. This approach has advantages in eliminating drag losses and "hot" parts; however, the requirement to carry a fluid excess, the tankage size and weight, and the developmental status of the concept ruled against its selection at this time. Figures 7 and 8 show assembly drawings of the proposed nozzle and jet vane system in steel and glass wrapped shell designs. The nozzle incorporates a single-billet graphite throat insert designed with an external taper fit to insure a compression preload.

The control requirements for the cluster of three 3-segment motors in a Saturn-type configuration were examined and are summarized in Table VII.

The ballistic performances of the various jet deflection type TVC systems under consideration are shown in Figures 9 and 10. Figure 9 is a plot of side force per nozzle divided by axial thrust per nozzle versus percent of maximum control force. The ordinate, percent of maximum control force, is a function of each system's control producing parameter (i.e. jet vane deflection angle, secondary injectant flow ratio). The control parameter is listed for each system. These curves vary somewhat with each particular geometry and application, but the departure from these curves is in general not significant.

The motor control systems which were analyzed with regard to control force producing capability are jet vanes, secondary fluid injection, hot gas injection, and aerodynamic vanes.

Details of the jet vane design are shown in the appendix.



NOTES:

1. STEEL TO BE A.I.S.I. 4130 HEAT TREATED
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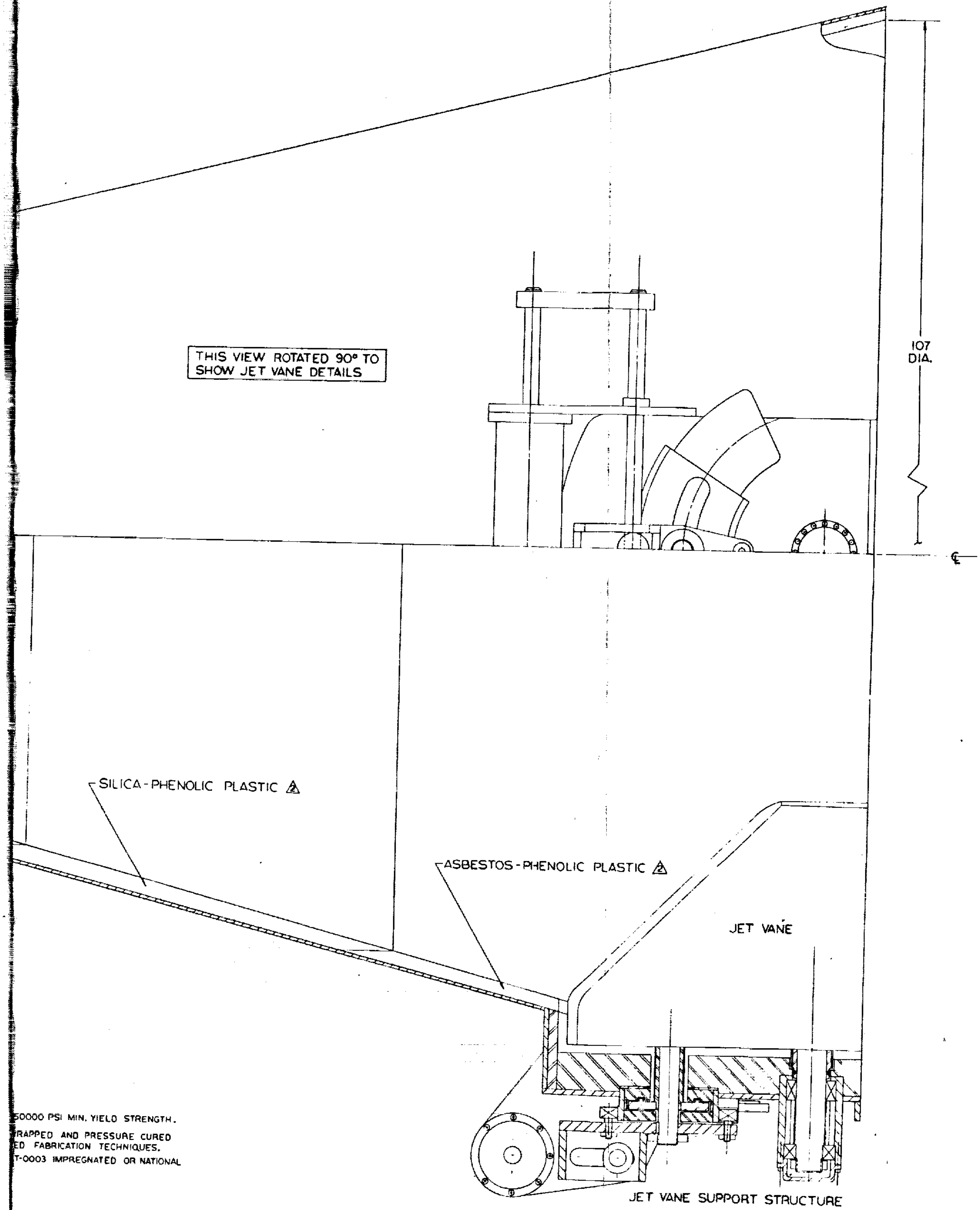
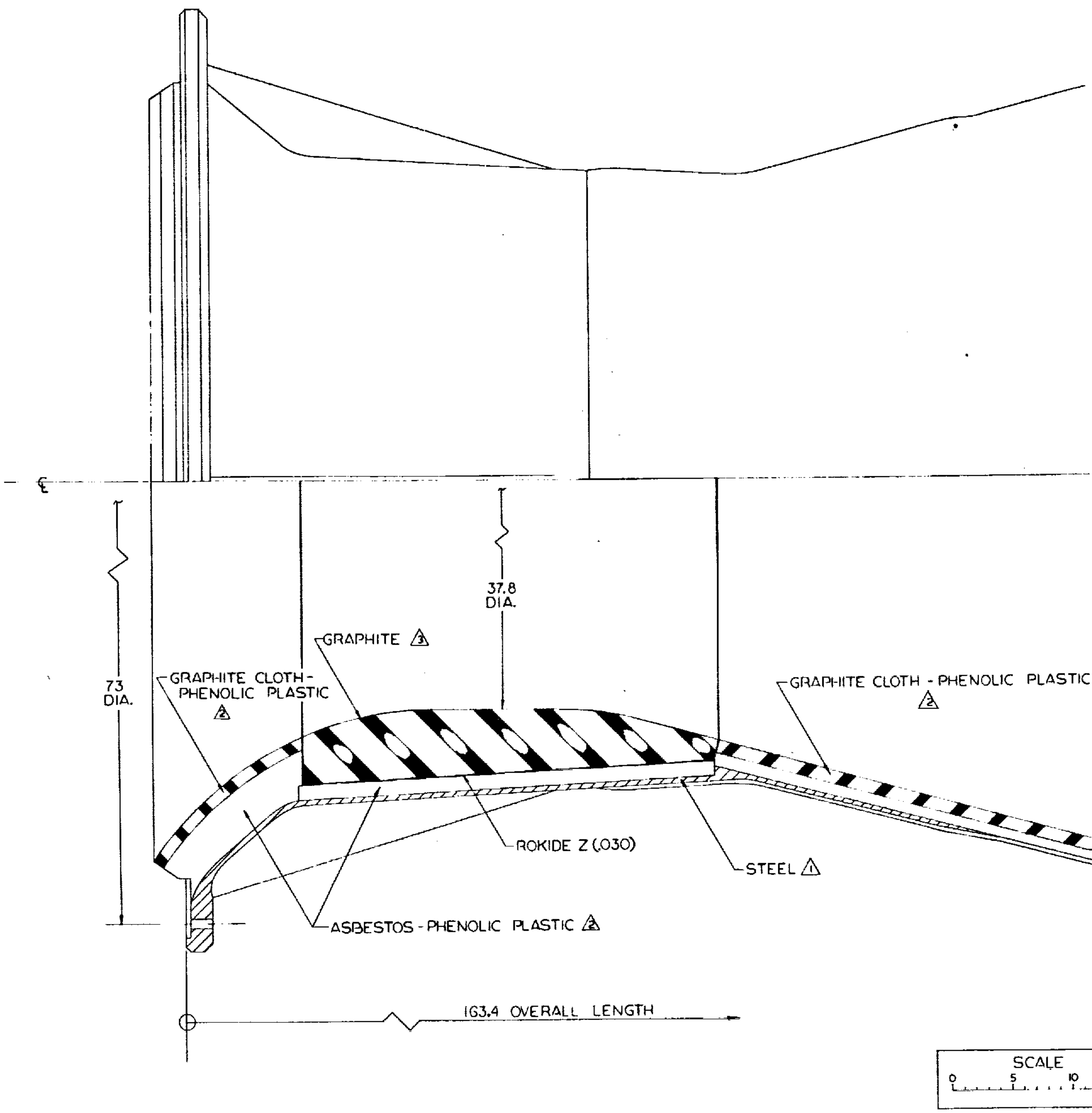


Figure 7 Jet Vanes Mounted on Large Steel Shell Nozzle



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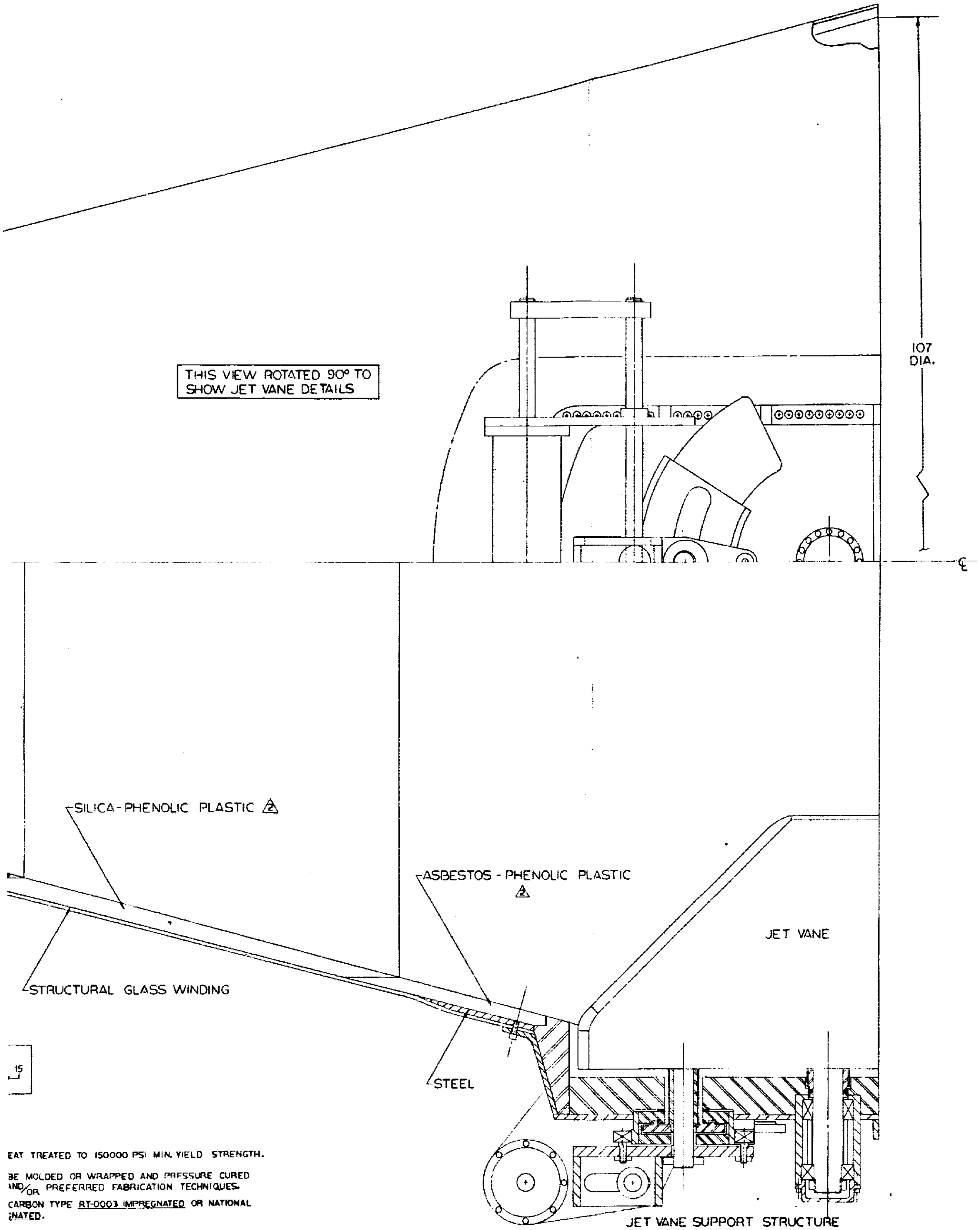


Figure 8 Jet Vanes Mounted on Large Glass-Wrap Shell Nozzle

FOLDOUT FRAME

TABLE VII

CONTROL FORCE REQUIREMENTS

Assumptions:

Thrust Misalignment = $1/4^{0}$ (3σ)

Center of gravity offset = 0.35 in.

Forces Required (lbf):

1.	Total normal force for wind shear (50 ft/sec/1000 ft shear at max Q)	41,500
2-a.	Total normal force at 1.5^{0} angle of attack	62,000
-b.	Total normal force at 1.0^{0} angle of attack	41,750
3.	Total normal force for CG offset	3,100
4.	Total normal force for thrust misalignment	21,000
5.	Total force at nozzle center line for roll control of thrust misalignment	12,000

(Force perpendicular to line from center line of vehicle to center line of nozzle)

Total Required Impulse (lbf-sec)

Total for correcting center of gravity offset =	95,000
Total for correcting thrust misalignment =	800,000
Total for correcting roll due to thrust misalignment =	440,000
Total for correcting 1^{0} angle of attack for the full burning time =	1,340,000

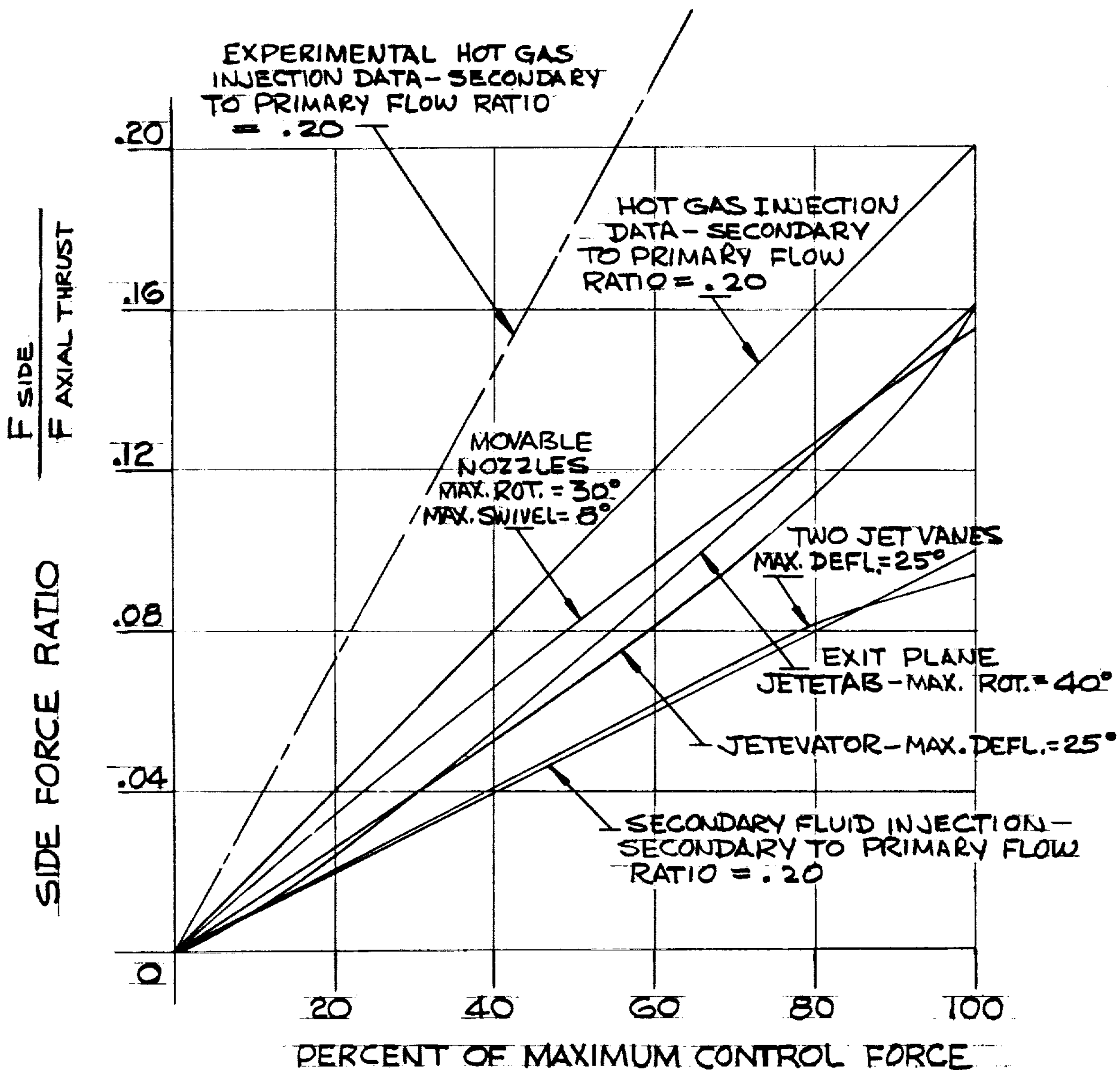


Figure 9 Thrust Vector Control Performance Characteristics, Side Force Ratio

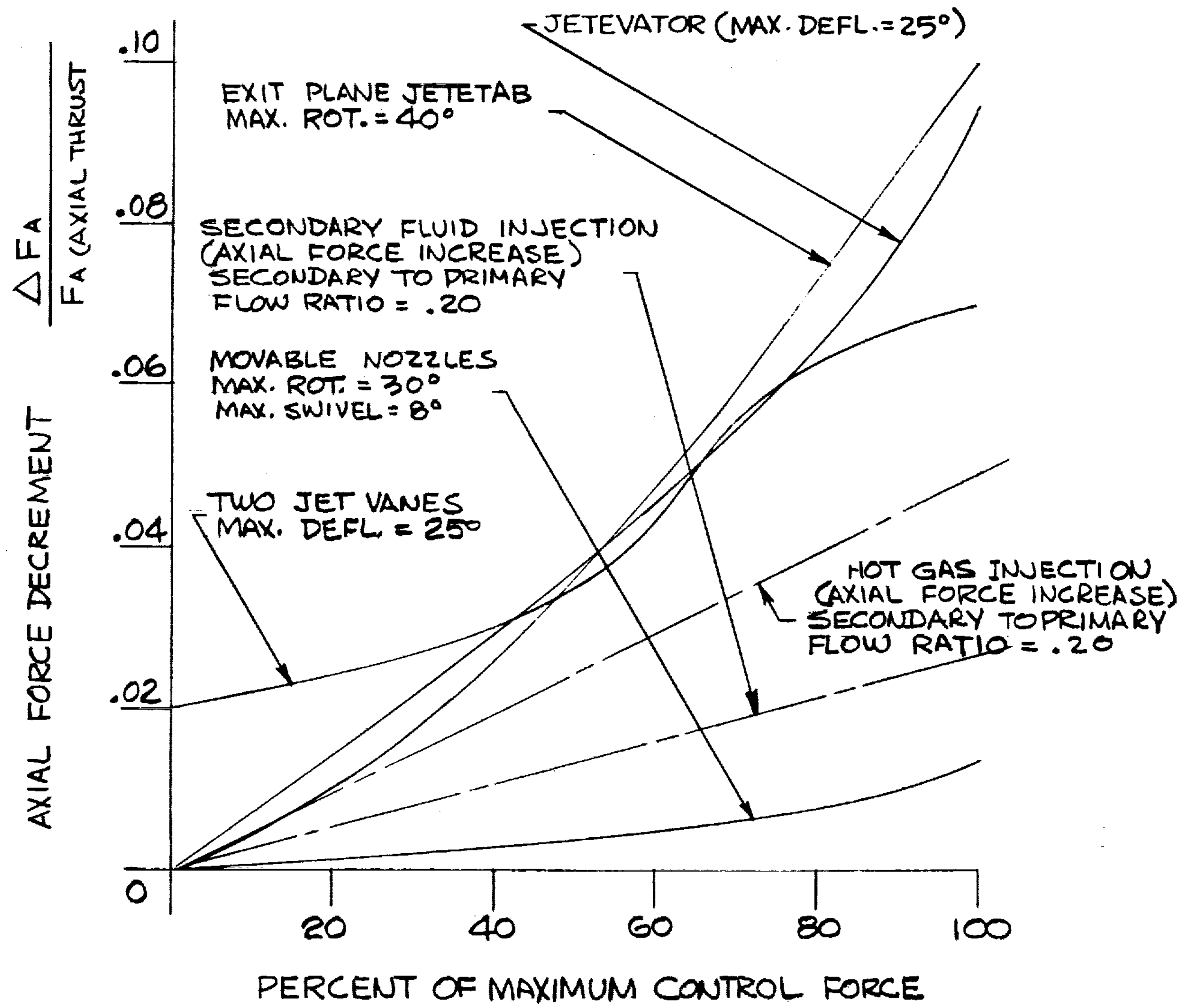


Figure 10 Thrust Vector Control Performance Characteristics, Thrust Decrement

C. Insulation Design

The insulation material chosen - silica-filled Buna-N rubber - has been used extensively in the ballistic missiles programs. An analysis of two methods of application, layup in uncured sheets versus cementing in of premolded sections favored the former due principally to better flexibility for dimensional changes during the development program, superior case bonding, better insulation homogeneity, and lower tooling costs. The required thicknesses of insulation would be determined from post-firing examination of over-insulated R and D static tests but would still maintain a wide safety margin.

D. Grain Design and Interior Ballistics

The propellant configuration recommended for the NASA Booster is a segmented case-bonded grain having a simple circular port. The circular perforation cross section was chosen for the reason of minimized grain stresses. Any convoluted design creates points of propellant stress concentration and greatly increases the chances of malfunction. The ends of the segment grains are uninhibited and are permitted to burn throughout the duration of firing. This is done to provide the most reliable and reproducible performance curve possible. If these surfaces were partially or completely restricted, an unnecessary point of potential unreliability would be introduced. The additional amount of case insulation required is not significant. A convoluted port design is not required because relative pressure progressivity or regressivity can be easily controlled by adjustment of the segment length-to-diameter ratio (l/d).

The propellant in both the forward and aft domes is fully released from the case to permit thermal contraction of the grain without overstressing the liner-propellant bond. The grain surface adjacent to the domes is inhibited with a "floating boot".

A step is provided in the forward head section grain design to provide:

(1) Longer thermal radiation protection to the forward head insulation.

(2) 4000 pounds of additional propellant.

No danger of grain cracking at this transition is anticipated since the forward grain surface is stress-relieved.

A segment propellant l/d ratio of 1.4 has been chosen to provide the desired performance regressivity, but this requirement could change in accordance with the specific mission criteria. For example, an even more regressive curve may be desired if dynamic loading at first staging is excessive.

The port-to-throat area ratio for the 3-segment design is 1.94 and for the 5-segment design is 1.63.

Figures 11 and 12 show the predicted pressure and thrust versus time performance curves for the 3-segment and 5-segment designs respectively. The curves are idealized to the extent that they do not consider erosive burning or nozzle throat erosion, and the thrust curves are calculated to sea level performance rather than over the actual flight path.

Based on payload trade-off values for specific impulse and mass fraction improvements, calculations to determine the optimum chamber operating pressures of the 3-segment and 5-segment boosters were made. Figure 13 is a plot of the results. Pressure vessel weights were assumed to vary directly with chamber wall thickness, which is valid for a design having low bending moments in the joints. The design altitude assumed (20,000 ft) was that at approximately one-half burn time.

Since the optimization curve is relatively flat, however, other considerations may influence the selection of average operating pressure. From the standpoints of interchangeability of segments and flexibility of application to various missions, it would obviously be desirable to have the two motors designed to the same pressure. Also, as shown in Figure 5, page 13, the higher pressure level would permit the motor to have a greater growth potential. At an average pressure of 1000 psi, for example, motors developing nearly 3 million pounds of thrust for 55 seconds could be built.

E. Ignition

The igniter design, shown in Figure 14, utilizes the pyrogen "finite duration" principle to provide a sustained and shockless ignition characteristic. The pyrotechnic proposed is ALCLO, a well-proven igniter mix containing a near-stoichiometric mixture of aluminum powder and potassium perchlorate. Figure 15 shows a curve of the predicted pressure-time igniter performance.

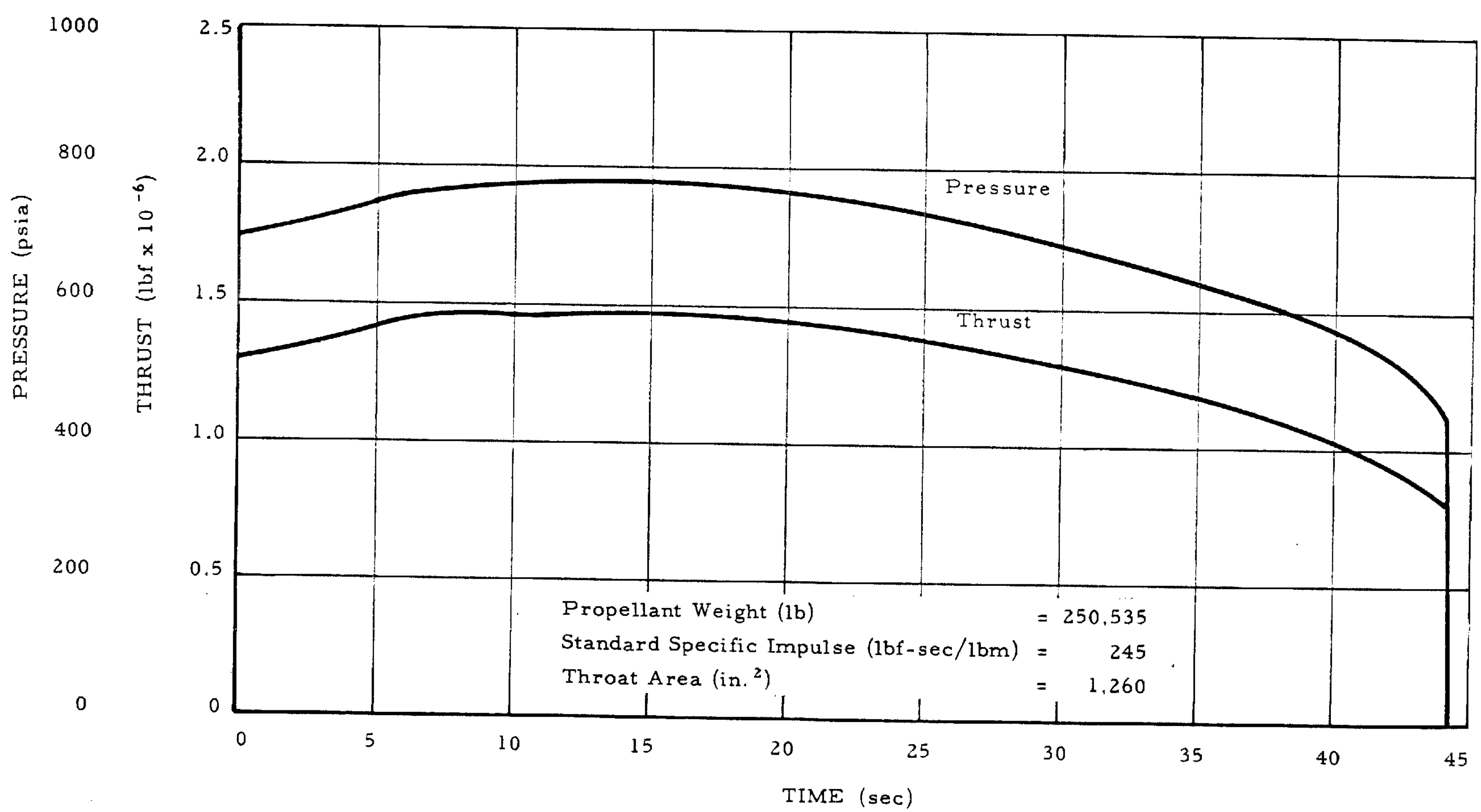


Figure 11 Estimated Pressure and Thrust versus Time, 3-Segment Booster

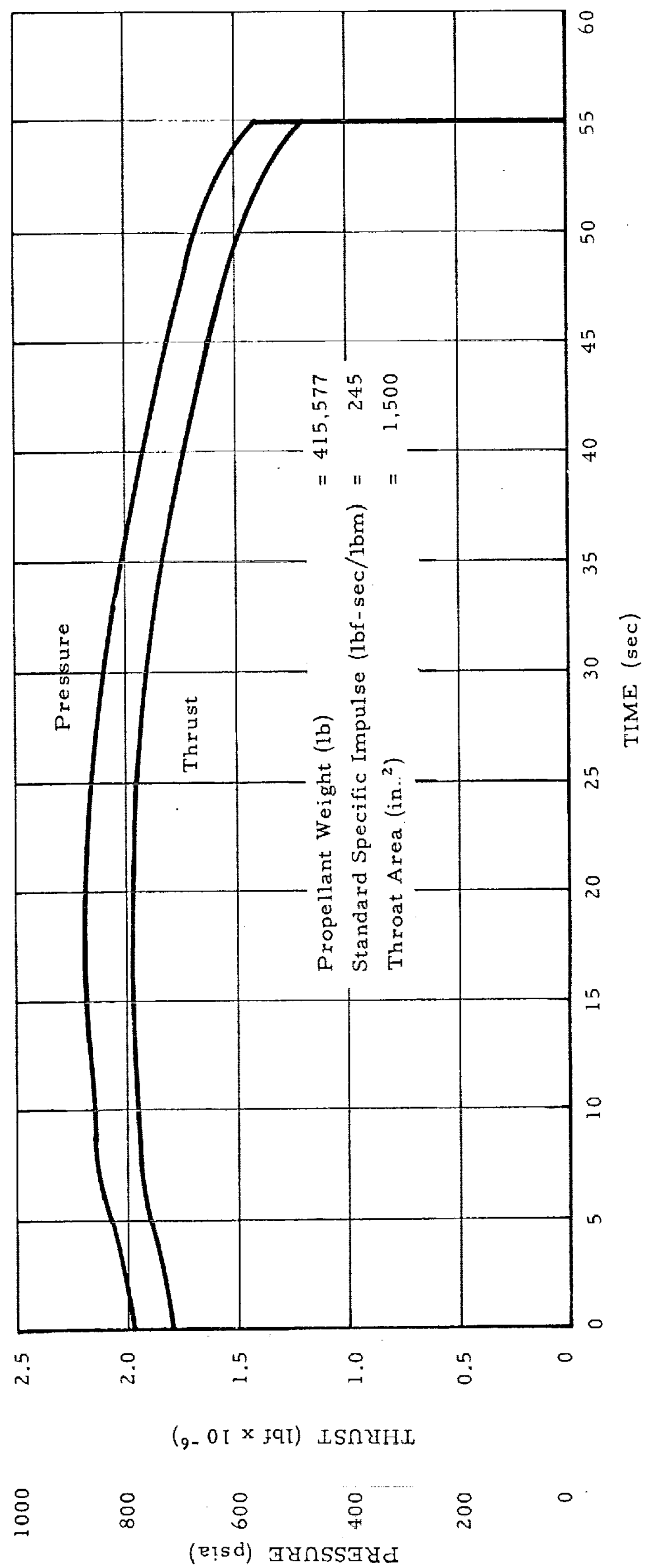


Figure 12 Estimated Pressure and Thrust versus Time, 5-Segment Booster

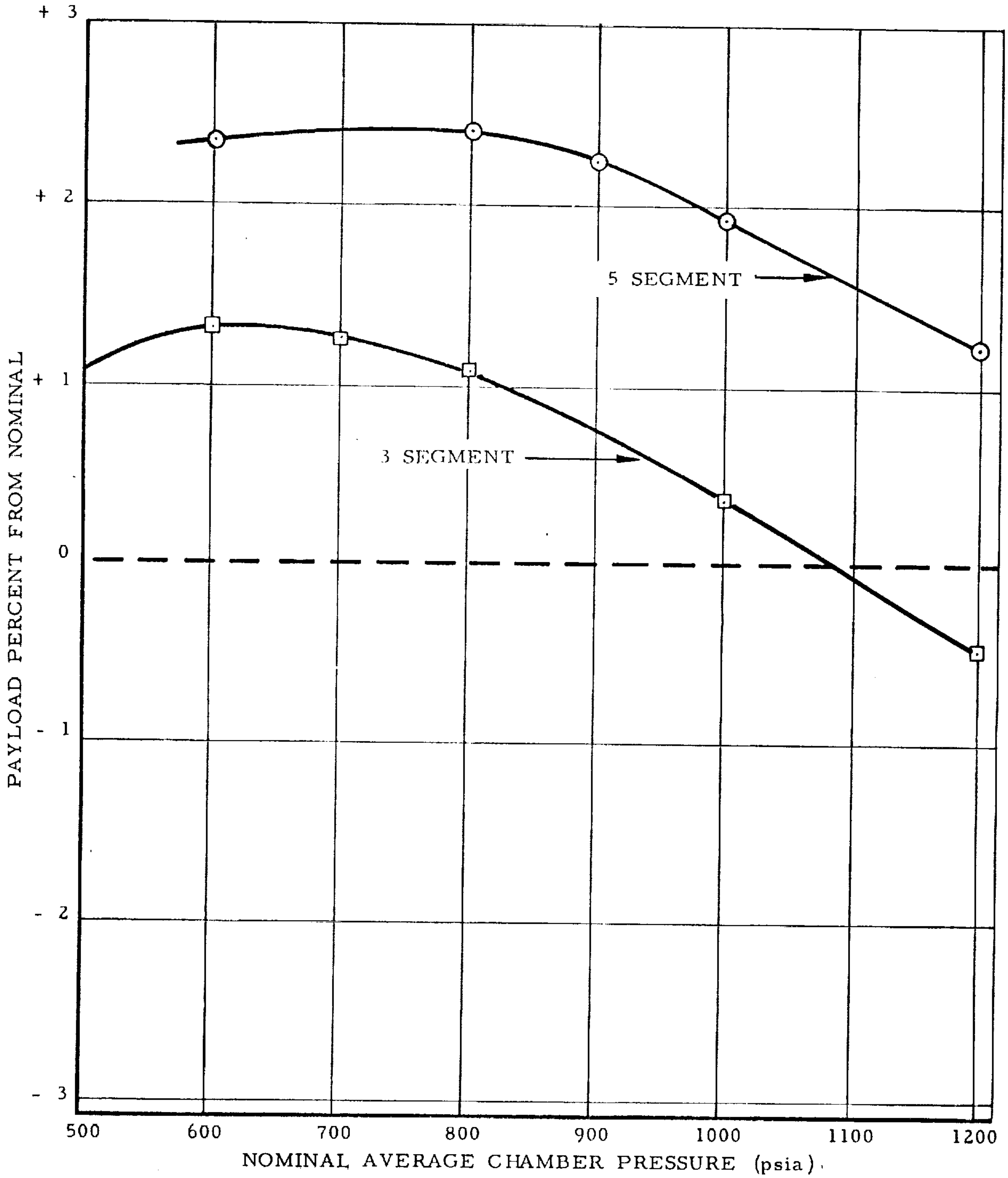
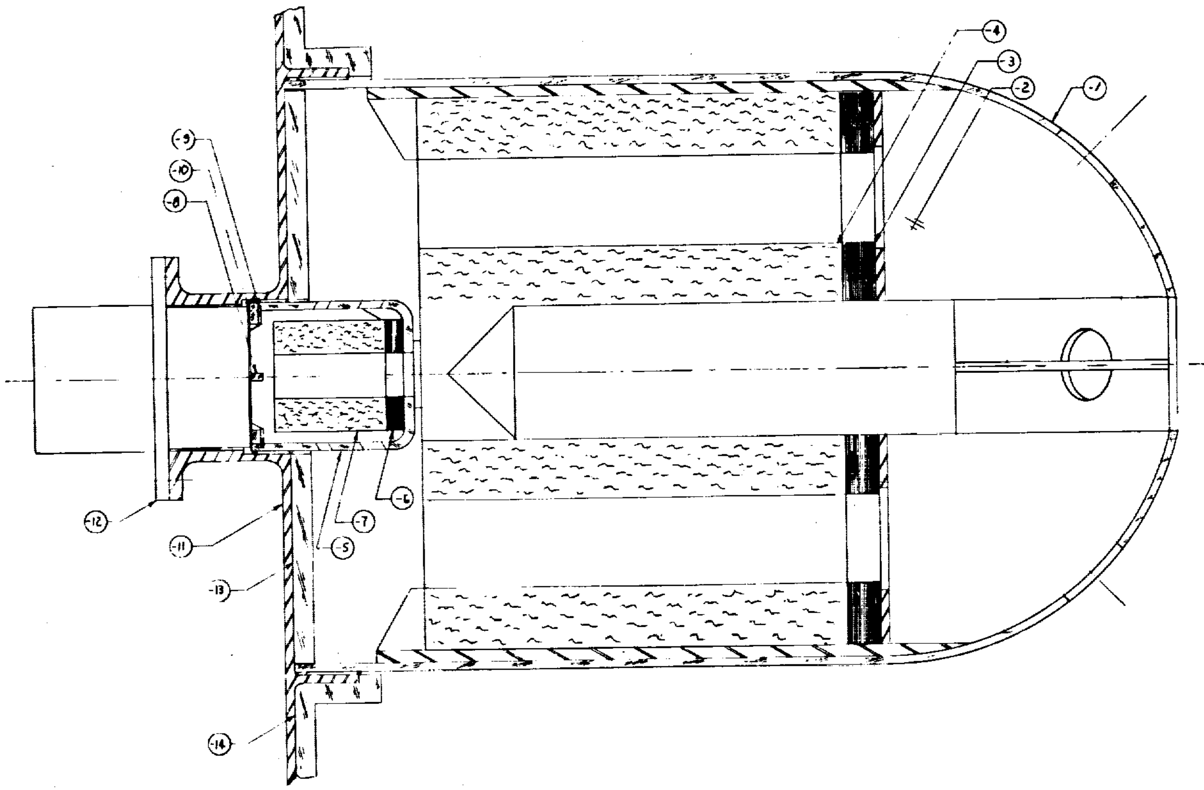


Figure 13 Booster Chamber Pressure Optimization



NO. REQ.	DETAIL NO.	
1	-14	INSULATION
1	-13	INSULATION
1	-12	SAFE ARM, ASSEMBLY
1	-11	DOME, MOTOR
1	-10	RING, INSULATION
1	- 9	SNAP-RING
1	- 8	SUPPORT, SLUG
1	- 7	SLUG, IGNITION
1	- 6	RING, VIBRADAMP SUPPORT
1	- 5	CASE, PLASTIC INITIATOR
4	- 4	SLUG, IGNITION
4	- 3	RING, VIBRADAMP SUPPORT
1	- 2	SUPPORT, STEEL SLUG
1	- 1	CASE, PLASTIC IGNITER

Figure 14 Igniter for NASA Booster

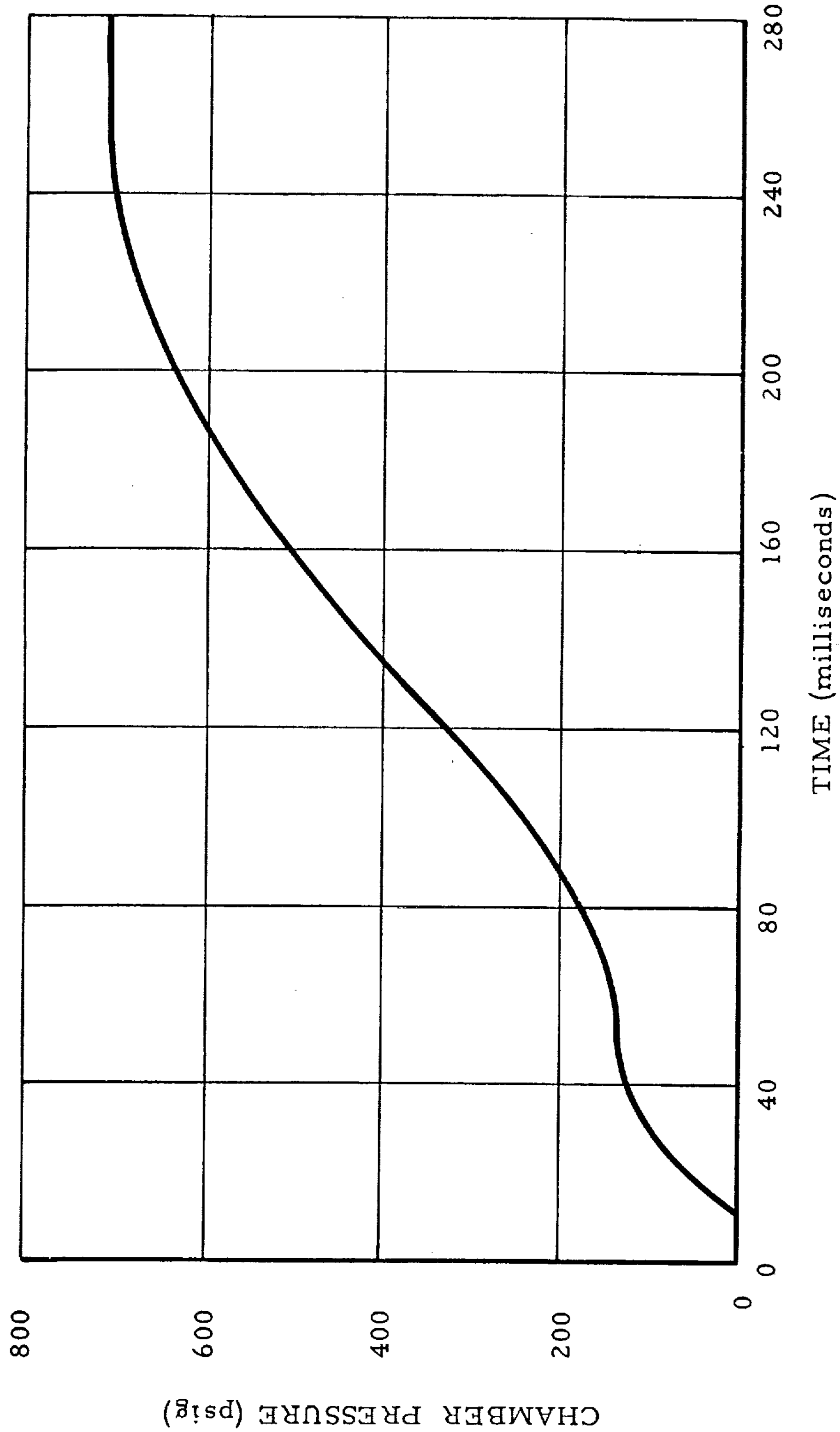


Figure 15 Predicted Ignition Pressure versus Time Curve

Ignition reliability and simultaneity among three clustered motors were carefully studied, using data from other large motor programs which used the identical design of igniter. In an expected ignition interval of approximately 200 milliseconds (time from fire switch to full chamber pressure) a standard deviation of less than 15 milliseconds is anticipated. Also, the pyrogen principle will permit the igniter charge to be substantially overdesigned without causing deleterious effects on the motor grain, resulting in a very high ignition reliability. Missile control during an ignition delay of one motor was investigated and found to be adequate. True redundant electrical circuitry will be used in the ignition train.

The safe-and-arm (S/A) and self-destruct mechanisms will be selected from those developed and proven in other missile programs. Only minor attachment and circuitry changes are expected to be required to adapt the devices to GCR specifications, permitting maximum advantage to be taken of previously established design data. Preliminary operational manual and electrical requirements for the S/A are given in the body of the detailed technical report.

While the use of shaped self-destruct charges was discussed in the detailed report, the final selection of a destruct method must consider the potential hazard to propellant detonation. It is recognized that shaped charges are capable of concentrating sufficient energy to endanger any propellant system, so precaution must be taken in design of such a device. Low energy devices promising failure at the chamber joints will also be evaluated.

F. Propellant and Liner Selection

1. Propellant selection. Propellant grain structural integrity studies conducted at GCR under sponsorship of the Army, Air Force, and NASA with GCR funding show that feasibility of very large diameter solid propellant motors depends significantly upon the availability of solid propellant with superior physical properties. Recognizing this, GCR embarked early in 1960 on an intensive corporate-sponsored research program to ensure success of the large solid booster motor concept by improving the well-established PBAA-type propellant to achieve the necessary physical, ballistic, and thermochemical characteristics. An aluminized, ammonium perchlorate propellant based on a binder of carboxylated polybutadiene was chosen because of the following advantages:

- Excellent mechanical properties.
- Delivered specific impulse in excess of 242 lb-sec/lb at 1000 psi and optimum sea level expansion.
- Relative insensitivity to moisture during processing and long storage.

- Excellent availability of raw materials.

- Virtual non-detonability of the cured propellant.

- Extensive background of successful application.

Analysis of the large solid booster motor design requirements showed that a propellant with the properties shown in Table VIII is required.

The GCR research program has resulted in a propellant, designated Polycarbutene R, which more than meets the large solid booster motor requirements. This is clearly evident when the pertinent values in Table IX are compared with those in Table VIII. The desired propellant has been achieved by applying the relatively new imine-type curatives, tris(methyl aziridinyl) phosphine oxide (MAPO) and phenyl bis(methyl aziridinyl) phosphine oxide (PMAPO), to a highly developed, low-cost PBAA polymer of the type used in the PERSHING, NIKE-ZEUS and early MINUTEMAN programs.

In addition GCR has tailored a liner with outstanding adhesive and cohesive characteristics that are compatible with Polycarbutene R and a large number of candidate insulating materials and hard-base surfaces.

The success of the research program is presently being demonstrated in 36 tests at Grand Central Rocket of case-bonded 7 by 26-inch NIKE-ZEUS ballistic motors, each containing about 50 pounds of propellant. Motors of this size have been fired successfully over the temperature range from -60^{0}F to 170^{0}F. In contrast, similar motors loaded with conventional epoxy-cured PBAA or with CBAN propellant had low-temperature limits of about -20^{0}F and -5^{0}F respectively. These temperature limits were also predicted from structural analyses made at GCR. Thus, confidence in GCR's ability to apply Polycarbutene R successfully to large solid booster motors is based on actual motor tests over a wide temperature range as well as on sound structural analysis. Furthermore, detailed analytical investigations of the physical properties required to maintain grain integrity during the rapid pressurization of ignition (high strain rate) and during storage (long-term creep) indicate that the exhibited characteristics of Polycarbutene R are adequate for large solid booster motors.

In July 1961, upon receipt of hardware and tooling, a 36-inch subscale, segmented solid booster motor will be tested with Polycarbutene R to affirm the integrity of the case insulation and joint designs. This test-firing will also provide supplemental information on the characteristics of Polycarbutene R in large motors.

The Polycarbutene R binder meeting GCR specifications is available in tonnage quantities from American Synthetic Rubber Co. The imine curatives are available in more than adequate supply from Interchemical Corporation, which has developed these materials over the past ten years for other applications.

TABLE VIII

REQUIRED PROPERTIES OF PROPELLANT FOR LARGE SOLID BOOSTER MOTORS

Nominal Uniaxial Physical Properties at 75°F

True Stress (psi)	Strain at Maximum Stress (percent)
130	40

Ballistic and Thermochemical Properties

Burning rate at 1000 psi (in./sec)	0.50 to 0.70
Pressure exponent	0.1 to 0.4
Temperature sensitivity (%/F°)	0.15 maximum
Delivered I_{sp} at 1000 psi, optimum sea level expansion (lb-sec/lb)	245
Density (lb/in.^{3})	0.062 minimum

TABLE IX

PERCENT-BY-WEIGHT FORMULATION AND CHARACTERISTICS OF POLYCARBUTENE R PROPELLANT (GCR-544)

Nominal Composition (percent-by-weight)

Polycarbutene-R binder*	12.7
Imine curatives*	0.9
Aluminum	16.0
Ammonium perchlorate	67.0
Circo (light) oil	2.2
Parabar 441	0.2
Ferrocene	1.0
	100.0

Uniaxial Physical Characteristics

	True Stress (psi)	Strain at Maximum Stress (percent)
at -65°F	566	21
at 70°F	123	49
at 140°F	80	52

Ballistic and Thermochemical Properties

Burning rate equation	$r = 0.54\ (Pc/1000)^{0.36}$
$(\pi_p)_k$	= 0.12%/F°.
Delivered I_{sp} at 1000 psi, optimum sea level expansion, 7 by 26-inch motors (lb-sec/lb)	243
Density (lb/in.^{3})	0.062

Sensitivities

Autoignition temperature (°F)	487 (5 min)
Impact (kg-cm)	90

Processability

Pot life	6 hr at 135°F
Optimum cure	108 hr at 140°F

* Exact ratio of binder and curative is based on analysis of carboxyl and imine equivalents of each lot of raw materials.

2. Liner selection. The liner material for Polycarbutene R propellant in large solid booster motors has been selected, developed, and tested on the basis of an over-all motor analysis. Requirements for adhesion to propellant and inert parts, cohesiveness, resiliency, restriction capability, aging stability, and requisite processability have all been carefully assessed. Based on a thorough study, liner GCLX-53-124 has been selected. This liner is a carboxylated butadiene acrylonitrile terpolymer, cured with epoxide resins and filled with requisite percentages of oxidizer and carbon black. The fillers respectively serve to control the liner cure properties and to provide reinforcement. The formulation of GCLX-53-124 is as follows:

	Percent-by-Weight
Butadiene-acrylonitrile-acrylic acid terpolymer	42.76
Epoxide resin curatives	27.24
Ammonium perchlorate	19.00
Thermax carbon black	11.00
	100.00

This liner has been thoroughly evaluated in peel tests and bond-jig tests against Polycarbutene R propellant and also against a variety of metals and insulating surfaces commonly employed in motor construction. In many tests of the liner-to-propellant bond, failure consistently occurred within the propellant matrix, demonstrating integrity of the adhesive bond over a wide range of temperature. Adhesion to typical inert, hard-base surfaces tested to date is excellent; stresses required to cause bond failure are consistently greater than propellant failure stresses.

G. Trajectories and Flight Mechanics

The performance of Vehicle No. 1 was calculated by the IBM 7090 digital computer. During the process, cost data were constantly fed into the calculations with each design change in order to continue to direct the designs not only toward better payload capabilities but also to lower costs of the over-all system. The trajectory data for the one million-pound vehicle is presented in Figure 16. The data are also presented in tabular form in Tables X and XI. The trajectory followed was a gravity turn with zero lift trajectory until the dynamic pressure reduced to about 40 psf; then a programmed angle of attack was gradually applied until the vehicle reached an angle of attack of 1.5^0 at dynamic pressure = 0 psf. This program was followed until the vehicle reached orbital altitude, where an angle of attack was applied to maintain the given altitude until orbital velocity was achieved.

This vehicle is capable of placing 60,000 pounds in the 307 n.m. orbit and propelling 18,500 pounds to escape velocity. Figure 17 shows the payload capacity of vehicles using first stage motors of two to eight segments in clusters of three.

The total propellant capacity of the liquid fueled upper stages is utilized in the solid boosted Vehicle No. 1, but the total propellant capacity of the liquid tanks is not utilized on the Saturn vehicle because of first stage thrust limitations.

The nozzles have been canted approximately 5^0 so that the thrust of each motor passes through the center of gravity at burnout of the stage. This will eliminate overturning moments that would otherwise exist if the three motors do not burn out simultaneously. The motors are designed to have an average chamber pressure of 700 psi and a nozzle expansion ratio of 8.4. The weight summary of Vehicle No. 1 is shown in Table XII.

The ten million-pound gross weight vehicle, Vehicle No. 2, has two solid propellant stages and two liquid propellant stages. The first stage consists of sixteen motors of five segments each. The second stage consists of four motors of five segments each. The third stage is an H_2-O_2 propellant stage, roughly twice the size of Saturn S-II, but having six engines of 200,000 lbf each. The fourth stage of this vehicle uses H_2-O_2 propellant and has two engines of 200,000 lbf each. The fourth stage is the Saturn S-IV stage with two of the engines removed. The thrust levels of the third and fourth stages are near optimum for this particular vehicle and mission. The optimum take-off thrust-to-weight ratio is between 1 and 1.5 for the third stage and 0.6 and 1 in the fourth stage. The optimization curve is rather flat over these ranges. This vehicle has a payload capability of 130,000 pounds for escape velocity. The weight summary of Vehicle No. 2 is shown in Table XIII.

The payload capabilities and the general descriptions of the more important vehicles in the 10-million pound weight class considered are given in Table XIV. The three vehicles mentioned, in addition to Vehicle No. 2 which is the recommended design, were each rejected from detailed consideration for various reasons. Vehicle No. 3 was rejected primarily from the payload capability standpoint. A payload of approximately 130,000 pounds was desired. Also, it appeared that several other problems would result from the use of the Saturn S-I as a third stage for Vehicle No. 3.

Vehicle No. 4 was less efficient from a cost and weight standpoint than the recommended one, Vehicle No. 2. The second stage burnout acceleration would be over 6.5 g's, approaching the limits of upper stage structures. This vehicle also would present a considerable problem in clustering of the second stage unless a very low expansion ratio were used.

The third vehicle of the group, Vehicle No. 5, presented the same general problems as Vehicle No. 4. The acceleration at second stage burnout would be 7.4 g's. Furthermore, the payload capability was somewhat lower for this vehicle.

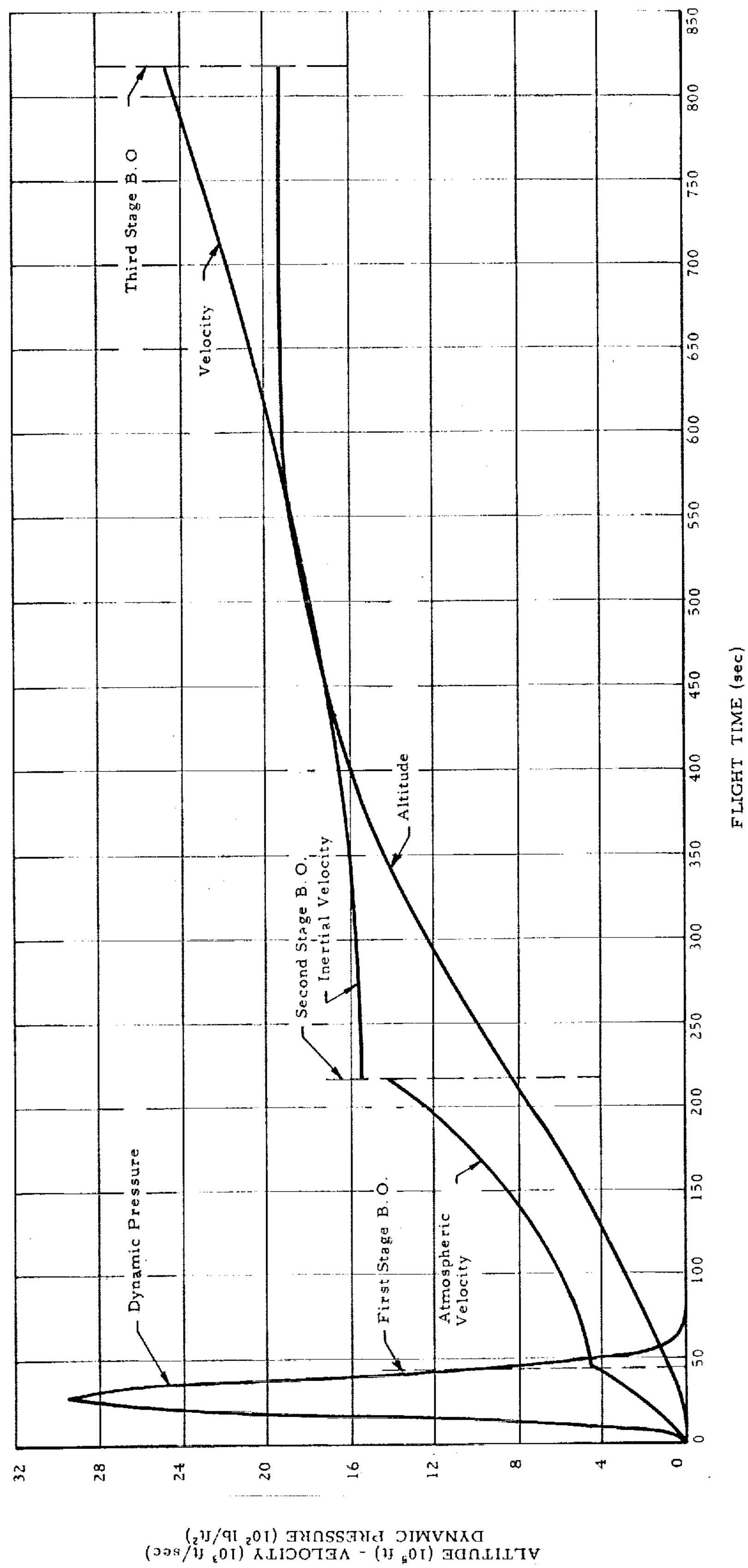


Figure 16 Altitude, Velocity, and Dynamic Pressure versus Flight Time, Vehicle No. 1

TABLE X

TRAJECTORY DATA, VEHICLE NO. 1

Time (sec)	Altitude (ft)	Atmospheric Velocity (ft/sec)	Inertial Velocity (ft/sec)	Range (ft)	Dynamic Pressure (lb/ft²)	Flight Path Angle (°)
0	5	0	1346	0	0	82.0
5	750	313	1461	170	114	74.6
11	3,900	800	1809	1,310	677	67.6
16	8,500	1240	2194	3,400	1415	64.0
26	23,400	2220	3137	11,600	2785	58.9
36	46,100	3343	4257	26,400	2446	55.4
45	75,900	4476	5399	48,000	1057	52.9
50	93,500	4565	5505	61,000	460	51.8
66	152,000	4962	5954	110,000	41	48.1
76	189,000	5251	6272	144,000	12	45.9
92	251,000	5800	6870	209,000	1	42.3
112	330,000	6582	7704	300,000	0	38.1
122	371,000	7042	8188	354,000		36.1
135	426,000	7700	8875	432,000		33.7
150	491,000	8542	9748	532,000		31.1
170	580,000	9837	11076	685,000		28.1
193	690,000	11656	12926	898,000		25.3
218.25	824,000	14207	15505	1,190,000		22.8
241	946,000		15568	1,480,000		21.2
261	1,045,000		15641	1,731,000		19.8
281	1,137,000		15733	1,984,000		18.5
300	1,224,000		15844	2,239,000		17.2
350	1,417,000		16197	2,891,000		14.0
402	1,586,000		16694	3,608,000		10.8
451	1,710,000		17270	4,307,000		8.1
500	1,805,000		17950	5,034,000		5.6
549	1,870,000		18735	5,794,000		3.5
602	1,910,000		19686	6,645,000		1.5
651	1,922,000		20687	7,488,000		0
700	1,922,000		21726	8,370,000		0
752	1,922,000		22979	9,372,000		0
801	1,922,000		24297	10,370,000		0
818.25	1,922,000		24787	10,729,000		0

TABLE XI

LONGITUDINAL LOAD FACTORS, VEHICLE NO. 1

Take-off First Stage	2.77
Maximum Dynamic Pressure	4.3
Maximum Load Factor	4.71
Burnout First Stage	4.14
Take-off Second Stage	3.87
Take-off Third Stage	0.4
Burnout Third Stage	0.91

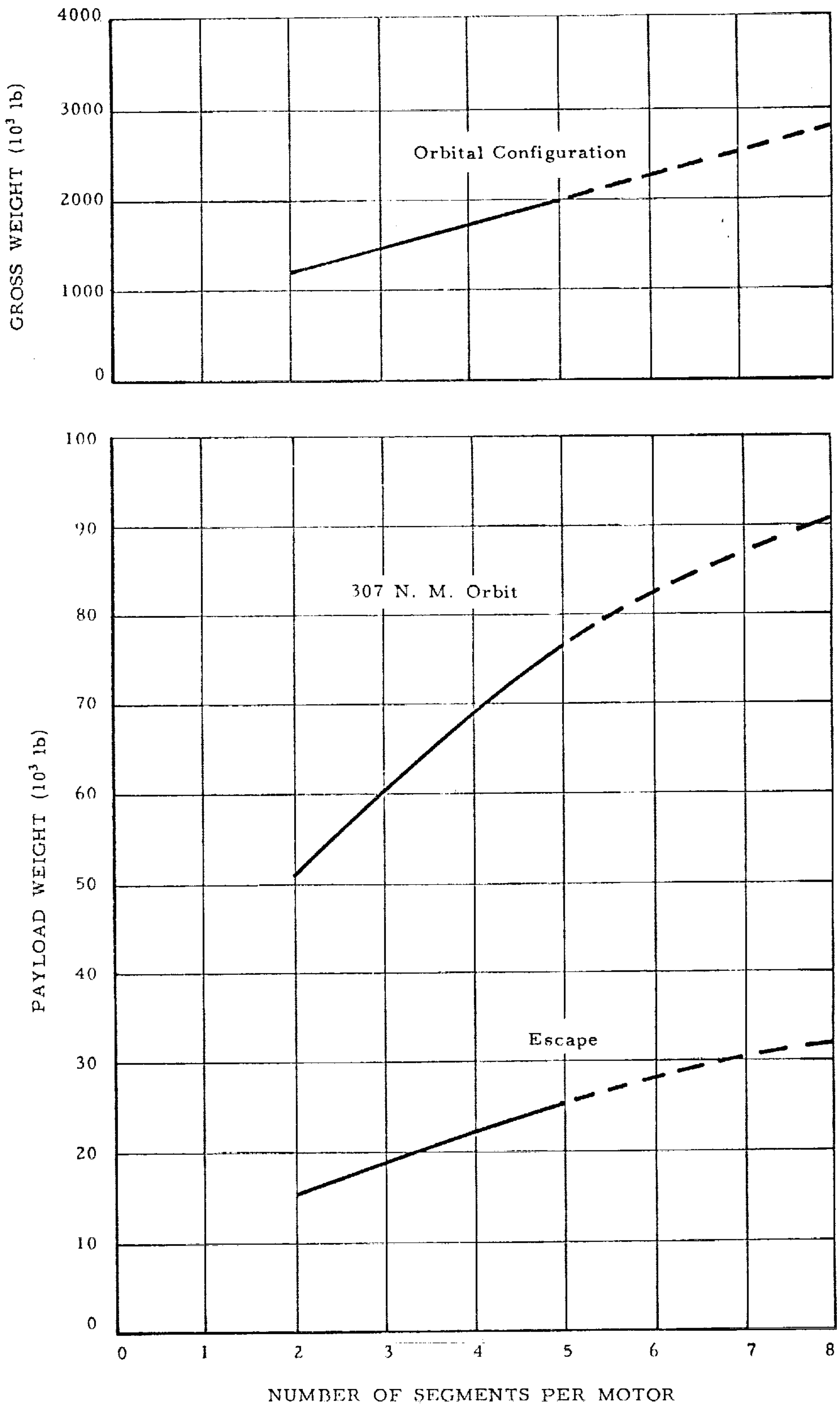


Figure 17 Payload Capabilities of Solid Boosted Three-Stage Vehicles (Cluster of Three Booster Motors)

TABLE XII

WEIGHTS OF VEHICLE NO. 1

ONE MILLION-POUND GROSS WEIGHT CATEGORY

		(lb)	(lb)
First Stage			
Propellant Weight		751,605	
Motor cases, nozzles, and controls		93,966	
Interconnect structure		9,000	
	Total		854,571
Second Stage			
Propellant (usable)		330,000	
Propellant residuals		4,940	
Airframe		16,390	
Engines		9,630	
Guidance and controls		500	
	Total		361,460
Third Stage			
Propellant (usable)		100,000	
Propellant residuals		5,440	
Propellant chill down		410	
Airframe		6,080	
Engines		2,500	
Guidance and controls		2,500	
	Total		116,930
Payload			60,000
TOTAL GROSS WEIGHT			1,392,961

TABLE XIII

WEIGHTS OF VEHICLE NO. 2, TEN MILLION-POUND GROSS WEIGHT CATEGORY

	(lb)	(lb)
First Stage		
Propellant	6,649,232	
Motor cases, nozzles, and controls	801,040	
Interconnect structure	64,000	
Total		7,514,272
Second Stage		
Propellant	1,662,308	
Motor cases including nozzles and controls	231,660	
Interconnect structure	24,000	
Total		1,917,968
Third Stage		
Propellant (usable)	660,000	
Propellant residuals	9,880	
Airframe	32,780	
Engines (6 at 2,407 lb)	14,442	
Guidance and controls	500	
Total		717,602
Fourth Stage		
Propellant (usable)	330,000	
Propellant residuals	4,940	
Airframe	16,390	
Engines (2 at 2,407 lb)	4,814	
Guidance and controls	2,500	
Total		358,644
Payload		130,000
TOTAL GROSS WEIGHT		10,638,486

TABLE XIV

OTHER VEHICLES CONSIDERED IN THE TEN MILLION-POUND GROSS WEIGHT CATEGORY

<u>Vehicle No. 3</u>

Gross Weight	7,282,145 lb
Stage 1	Cluster of 8 five-segment solid motors
Stage 2	Cluster of 5 five-segment solid motors
Stage 3	S-I modified for altitude operation
Stage 4	S-II stage
Payload	60,000 lb to escape velocity

<u>Vehicle No. 4</u>

Gross Weight	12,737,348 lb
Stage 1	Cluster of 16 five-segment solid motors
Stage 2	Cluster of 8 five-segment solid motors
Stage 3	A stage equal to two S-II stages
Stage 4	S-II stage
Payload	134,000 lb to escape velocity

<u>Vehicle No. 5</u>

Gross weight	12,542,618 lb
Stage 1	Cluster of 16 five-segment solid motors
Stage 2	Cluster of 8 five-segment solid motors
Stage 3	A stage equal to $1\frac{1}{2}$ S-II stages
Stage 4	An S-II stage
Payload	120,000 lb to escape velocity

A preliminary cost analysis was made to determine the relative merits of Vehicle No. 5 and the recommended Vehicle No. 2, and no significant difference was found. The differences on a dollars per pound payload basis were so small as to be in the order of accuracy of the calculations.

Separation or staging at relatively high dynamic pressures is considered a potential problem. The analysis of controllability shows that at staging an angle of attack of 5.6^0 can be tolerated. This analysis did not take into account the dynamics of the vehicle at separation, such as the pitching or yawing motions or the response time of the controls. If such a detailed analysis indicates that a problem does exist, a practical means of solving it is to minimize the time during staging when no control exists. One way to minimize this time is to begin the second stage engine start sequence prior to actual separation. The separation would be initiated during thrust buildup with the partial thrust blast of the second stage being vented between the first stage motors. No particular hazard is envisioned in this sequence as might occur with a first stage having liquid propellant tanks containing residuals.

Other ways to reduce dynamic pressure to a minimum are to program a regressive thrust-time performance curve and to fly somewhat steeper trajectories.

H. Missile Structures

The general approach to evaluating possible structures was to cluster the motors for each configuration in a manner resulting in the best compromise that minimizes structural weight, facilitates assembly, allows for the various loading conditions, and minimizes launch pad complications. Structure weights are based on detailed analysis of loads and the particular structural arrangement, but details of joints, attachment hardware and beam specifications were examined only in a general manner. For this reason further study is required to produce refined preliminary designs and weights.

The rigid body loads during flight were calculated for two conditions: (1) at the time of maximum dynamic pressure, and (2) immediately prior to stage separation. The flight data used were based on a preliminary trajectory that is reasonably close to the final trajectory. The maximum flight loads occurred at maximum dynamic pressure condition and the highest longitudinal load factor occurred just prior to stage separation. The maximum angle of attack considered was 3^0. Table XV shows the calculated loads and the bending moments for which the structure was designed. In addition, to these loads, the condition of one motor not thrusting with two motors at full thrust was considered in the design of the structure.

The lower end of the motor cases are designed to take the launch support loads and a spacing of one foot between motors was determined to be sufficient for assembly purposes.

TABLE XV

BENDING MOMENTS AND AXIAL LOADS, ONE MILLION-POUND GROSS WEIGHT VEHICLE

A. Maximum Dynamic Pressure

Conditions:

t = 35 sec

$\bar{q}$ = 2820 lb/ft^2

Mach No. = 2.65

Altitude = 35,000 ft

Thrust = 4,030,000 lb

Weight = 825,200 lb

n_x = 4.12 g

n_z = 0.34 g

α = 3^0

P_∞ = 498 lb/ft^2

Distance from Nose (in.)	Bending Moment (lb-in.)	Axial Load (lb)
354	13,005,000	681,000
526	24,811,000	1,163,000
751	34,354,000	1,169,000
1241	58,477,000	2,654,000
1426	49,885,000	2,664,000

B. Immediately prior to first separation

Conditions:

t = 46.4 sec

$\bar{q}$ = 692 lb/ft^2

Mach No. = 4.58

Altitude = 84,000 ft

Thrust = 3,000,000 lb

Weight = 669,980 lb

n_x = 4.34 g

n_z = 0.11 g

α = 3^0

P_∞ = 47 lb/ft^2

Distance from Nose (in.)	Bending Moment (lb-in.)	Axial Load (lb)
354	3,206,000	336,000
526	5,625,000	844,000
751	7,806,000	849,000
1241	12,000,000	2,414,000
1426	8,007,000	2,424,000

Figures 18 and 19 show the main elements of the interconnect structure. The adapting ring flanges are stiffened by local transverse webs for truss and beam load concentrations. In addition, the ring is supplemented by tie rods for radial loads. The central cluster fitting takes loads from the motors to the beams and ring so that the motors are not loaded radially.

Several arrangements of the first stage of Vehicle No. 2 having 16 motors were investigated in order to achieve one which would require the lowest total structural weight and also be symmetrical. The two most desirable arrangements are shown in Figure 20. Arrangement "A" was first selected as being most symmetrical and one which tends to minimize total cross sectional area. Arrangement "B" was selected, however, as the best from the standpoint of minimizing structural weight and is shown in more detail in Figures 21 and 22.

Three methods were considered for supporting this vehicle on the launch pad. These methods were examined sufficiently to determine the most desirable from the vehicle support structure standpoint.

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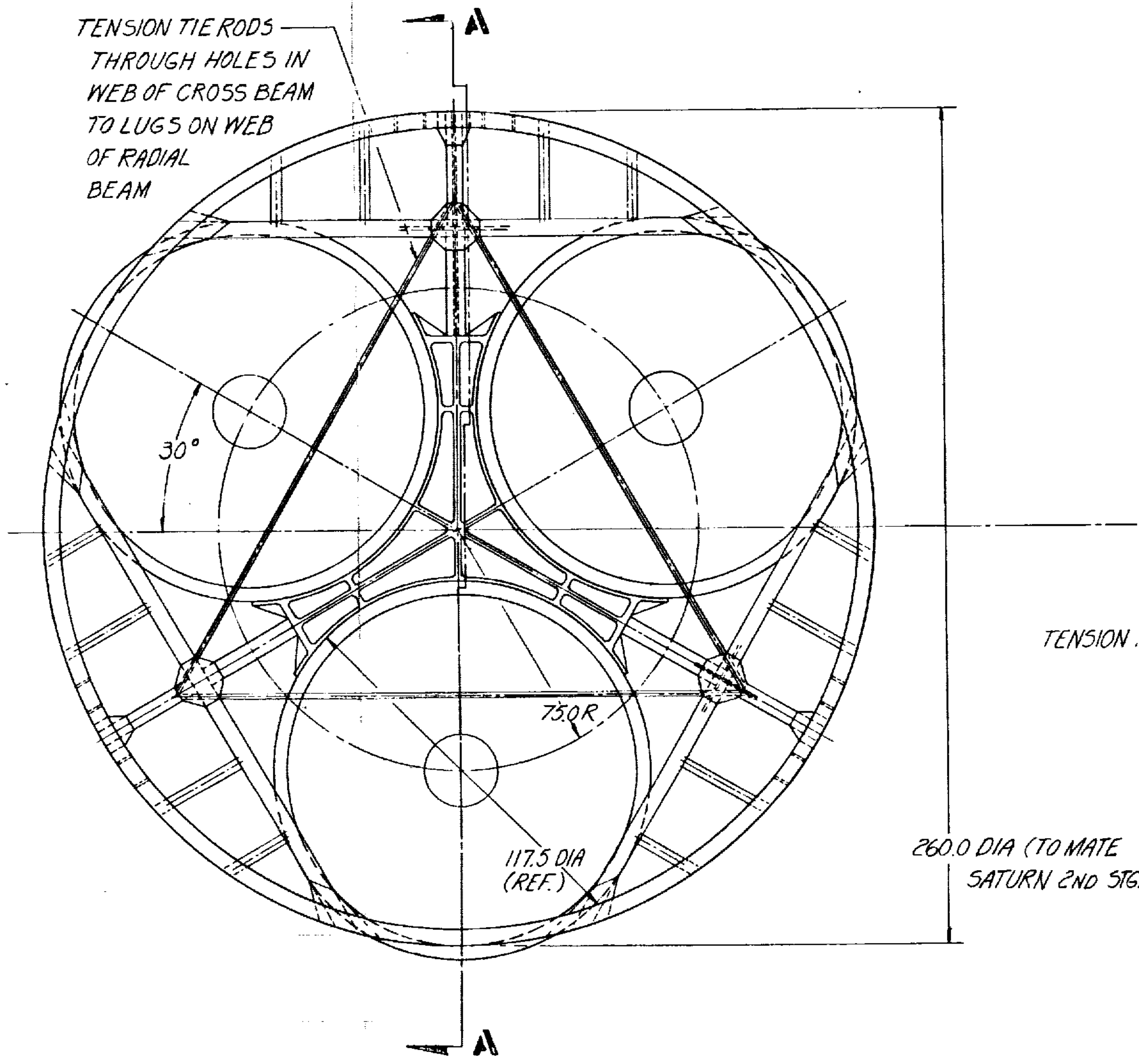

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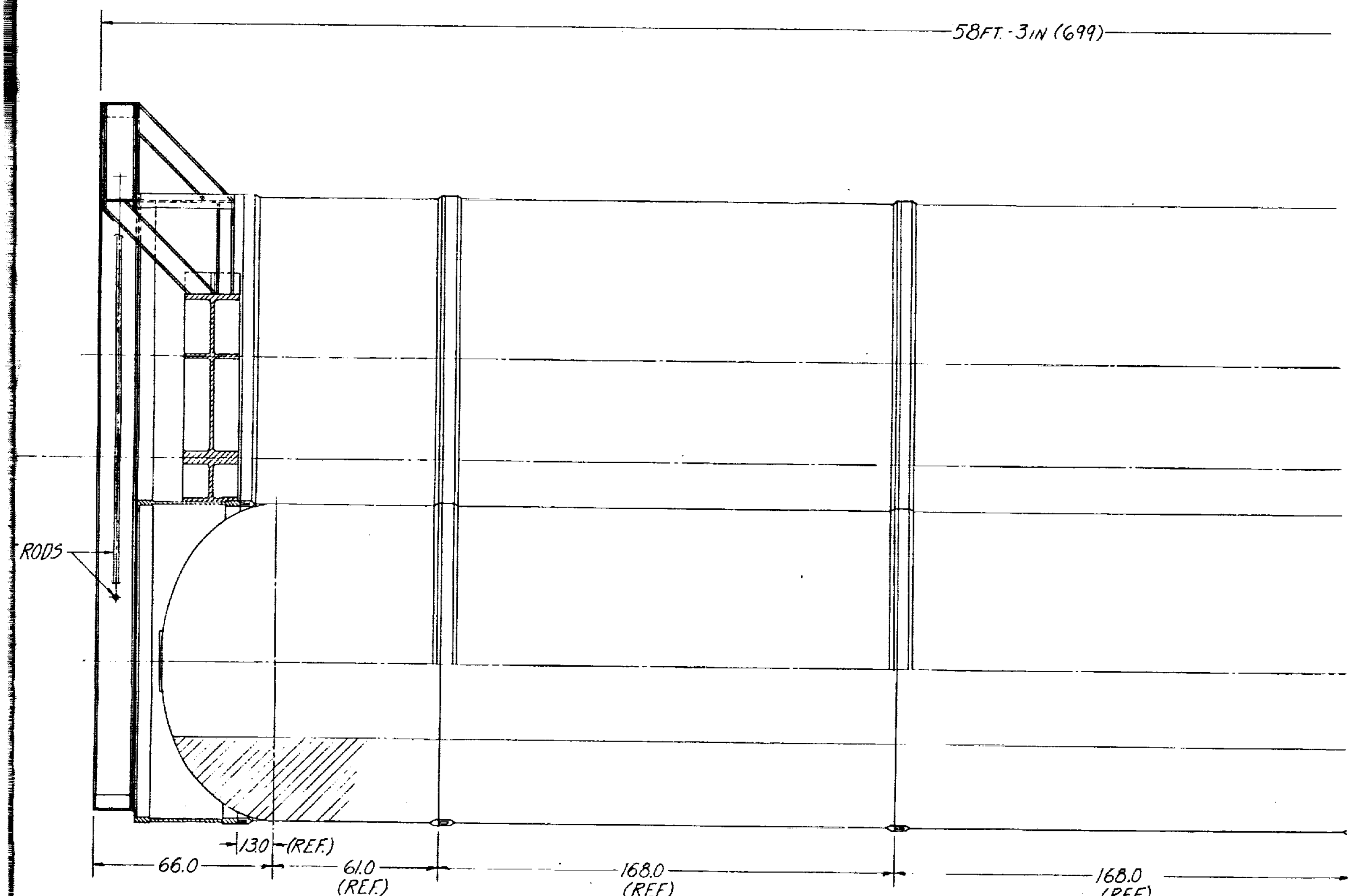
Figure 18 Three-Motor Cluster, Head End



PARTIAL SECTION A - A

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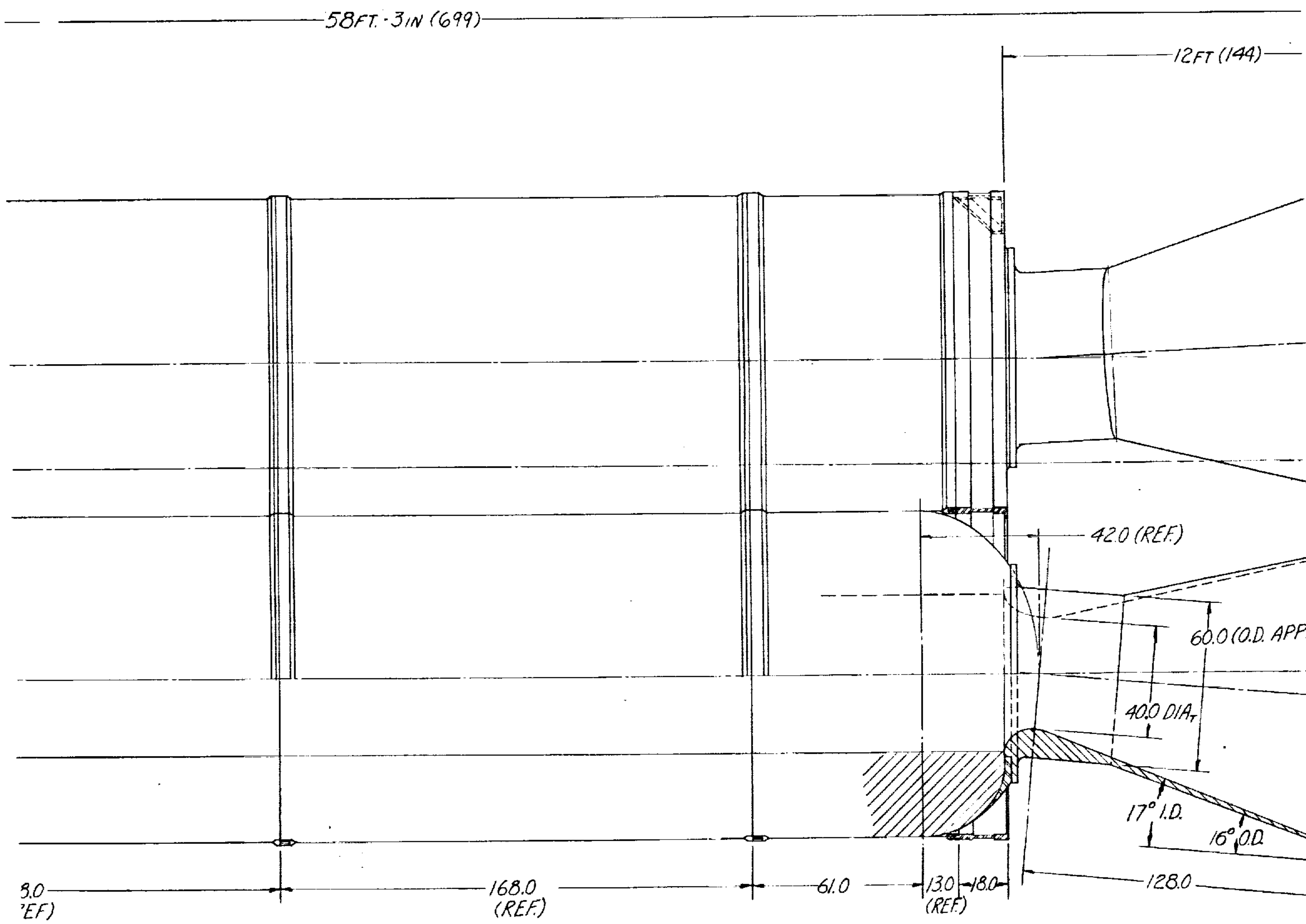

PARTIAL SECTION A - A

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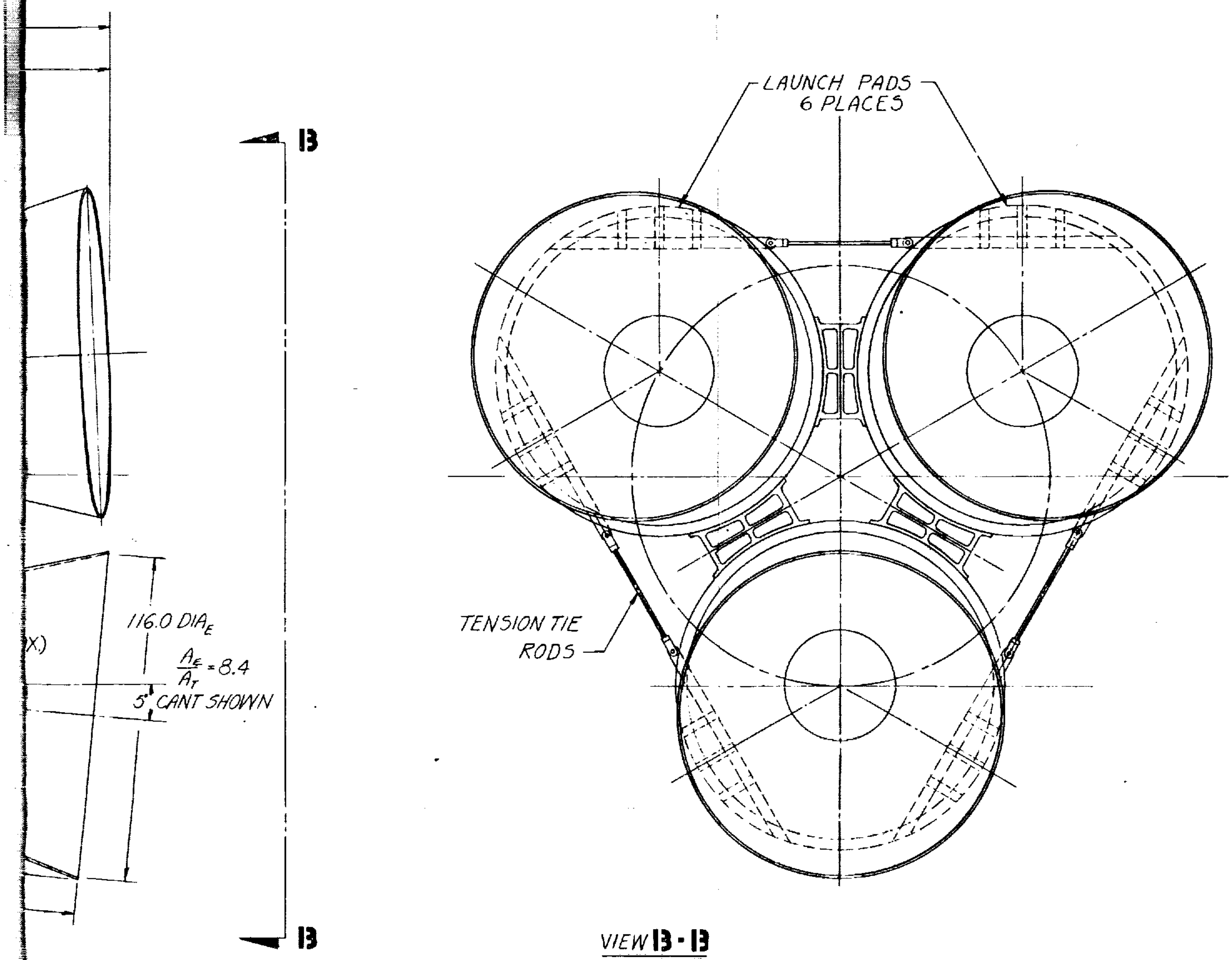

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Figure 19 Three-Motor Cluster, Nozzle End

I. Reliability

While missile system component reliability requirements can be positively established as needed to provide a given level of over-all missile reliability, reliability estimates such as are presented herein can be determined only intuitively and subjectively. Reliability estimates are created by systematically examining such factors as engineering complexity (number of parts and their functions) and state-of-the-art extension and by applying knowledge of designs and experience in the field. During a development program, the best reliability estimate may well be above the maximum demonstrable reliability.

The Grand Central Rocket design concept has been kept very simple. The simple grain, nozzle, and thrust vector system are ideally designed to permit careful inspection. Possibility for human error (the biggest source of unreliability) has been almost completely designed out by superior inspection techniques. Design margins for safety and performance are high. Maintenance and repair should be almost nonexistent. Consequently, success at an early period in the development program is almost guaranteed and is certainly well within the scope of the program outlined.

High reliability in service of the motor cases can best be assured by a severe hydrostatic test program. Metal fatigue, however, must be considered in choosing the hydrotest level. A hydrotest pressure level of 90 percent of yield (design) pressure is proposed for the NASA Booster cases. A hydroburst attrition rate of approximately 10 percent is expected. Use of this high hydrotest pressure level will provide an expected in-service failure rate of fewer than 1 in 10,000 cases.

Grand Central Rocket endorses the approach to solid propellant rocket reliability advocated by Space Technology Laboratories* whereby the motor is divided into the following basic subsystems:

(A) Case, insulation, and liner

(B) Nozzle and thrust vector control

(C) Propellant charge and igniter.

By a technique of pre- and post-test exclusions wherein one or more subsystems may be eliminated from the over-all reliability determinations due to a highly developmental status of the component, the maximum number of meaningful samples may be derived from a developmental test series.

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*Lipow, M. and Lloyd, D.K.
"Reliability Demonstration Program for MINUTEMAN Engines"
TR-59-R002-00548 (STL), September 1959.

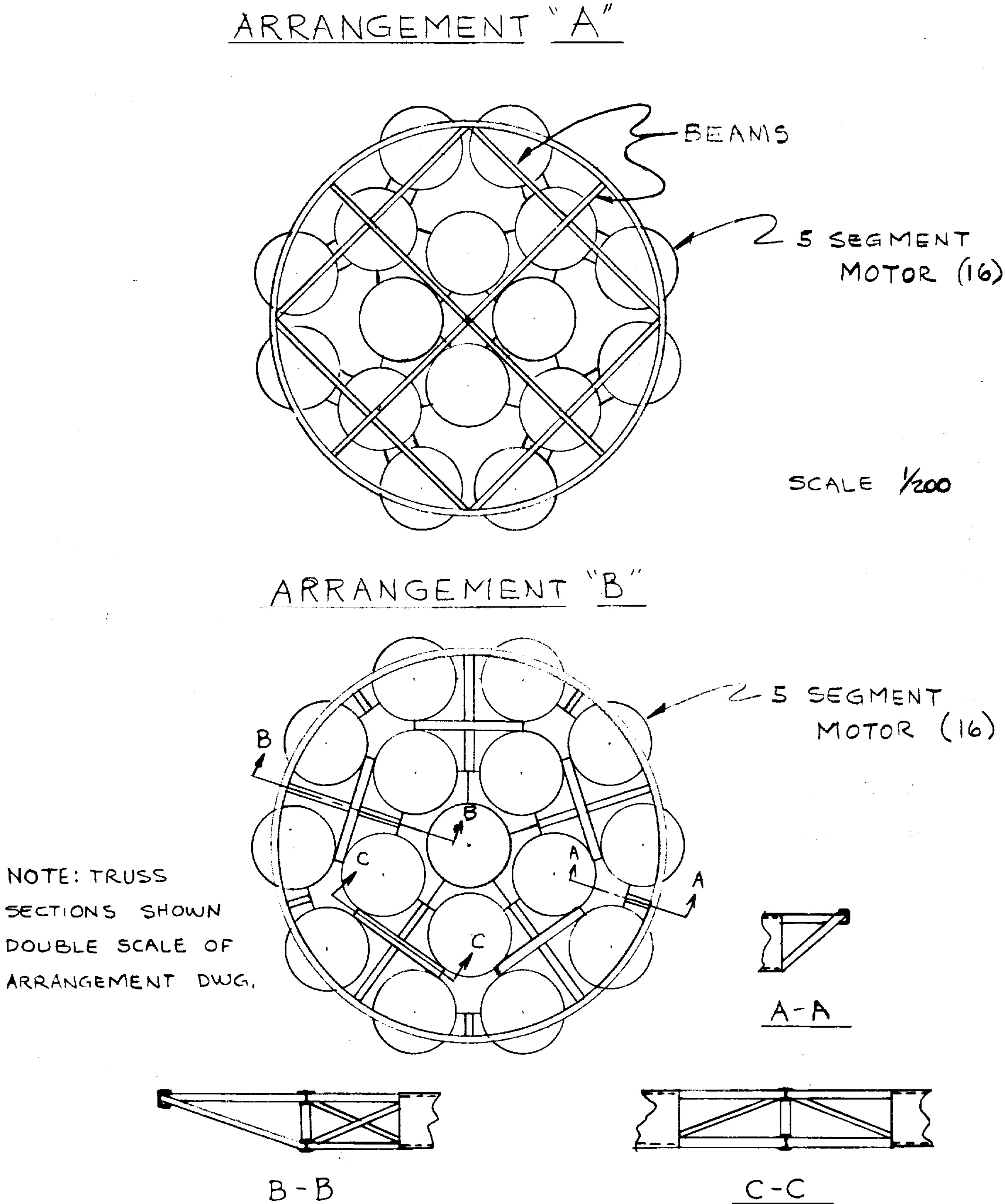

Figure 20 Sixteen-Motor Cluster Arrangements

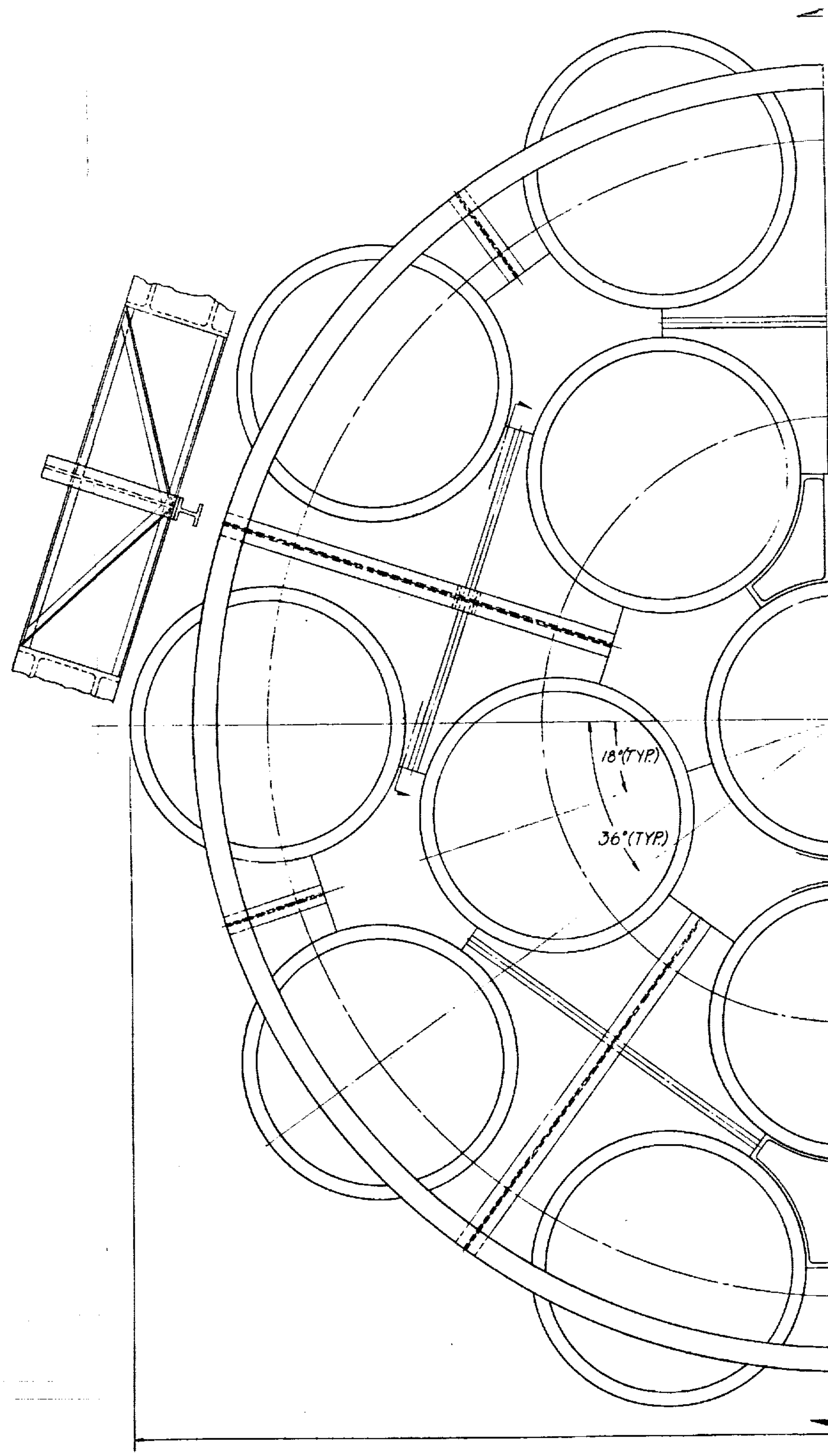

Figure 21 Sixteen-Motor Cluster, Head End

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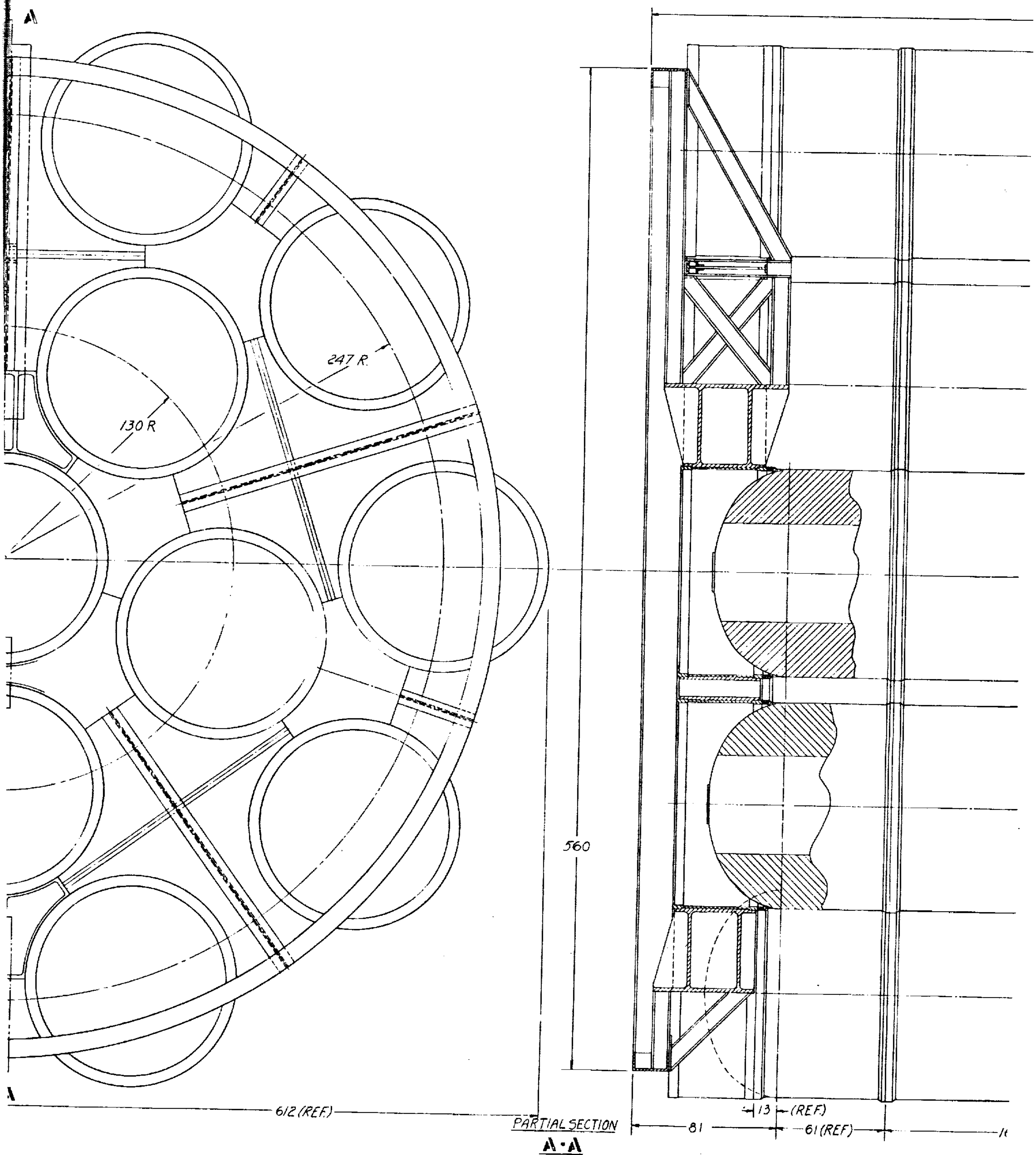

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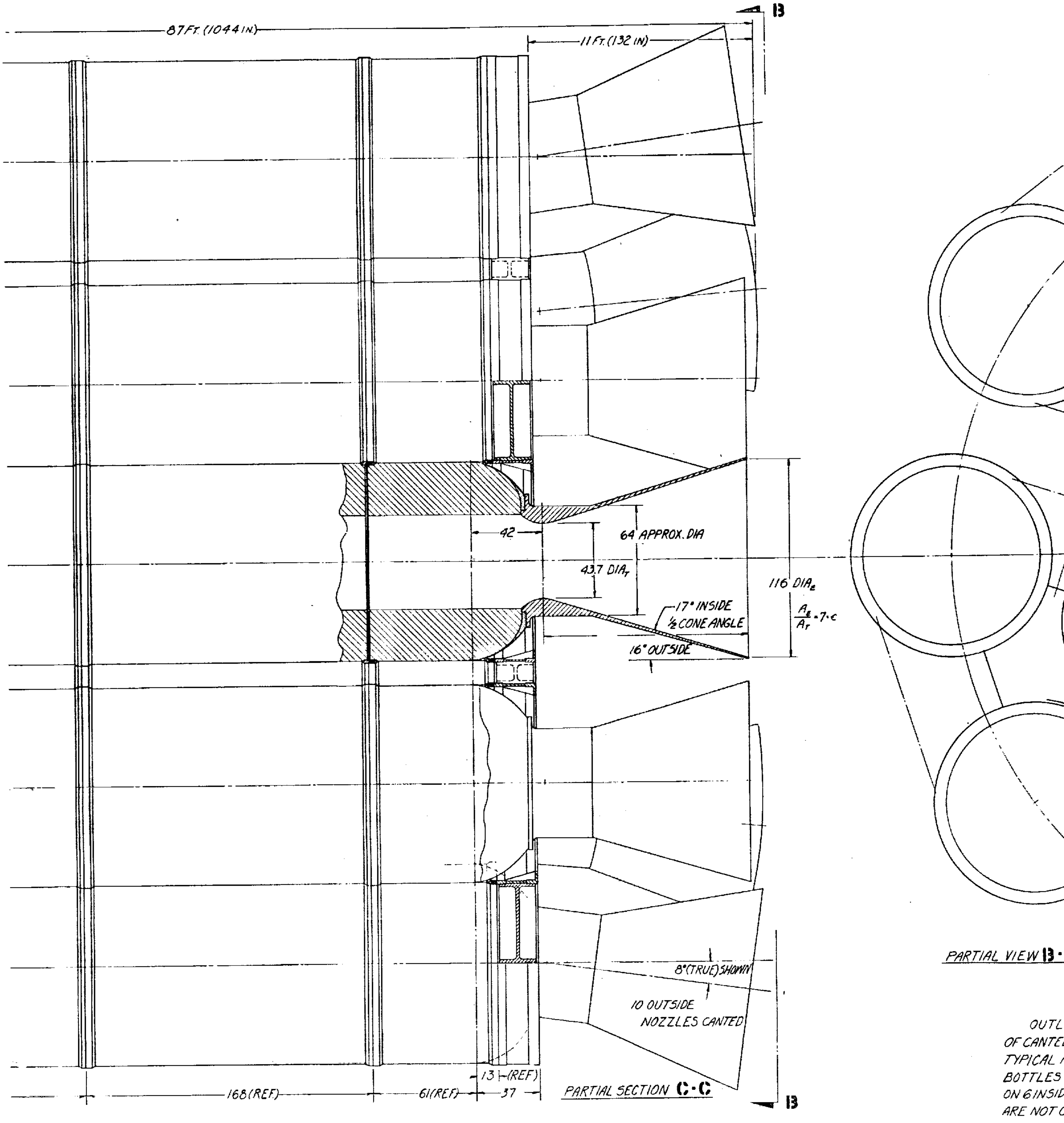

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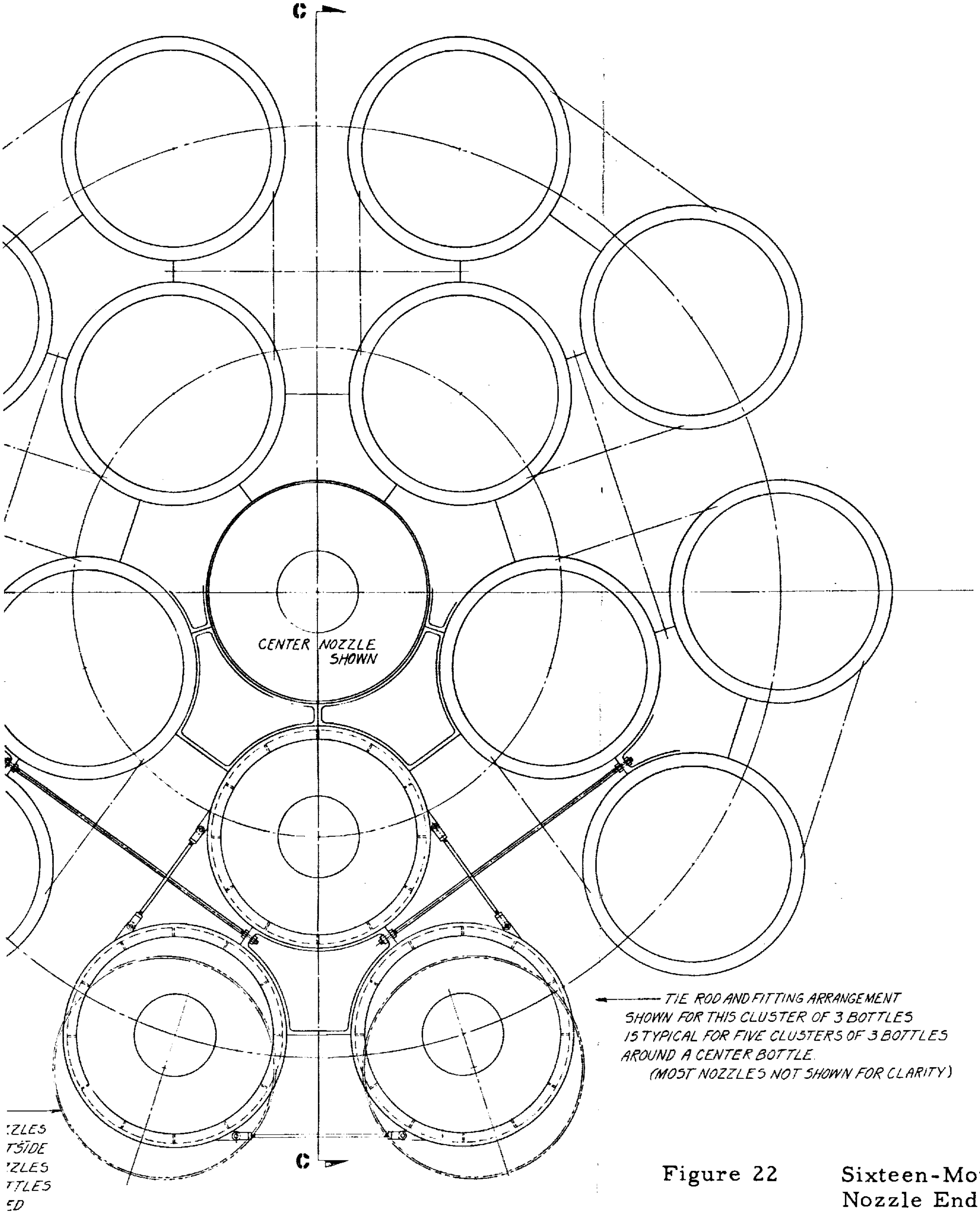


Figure 22 Sixteen-Motor Cluster, Nozzle End

By considering early development estimated reliabilities of the three subsystems of 96.1%, the reliabilities of the 3-segment booster motor would be:

Critical failure*	Major failure**
88.7% reliability	72.9% reliability
90.0% confidence	90.0% confidence

It should be noted that the foregoing numbers are minimum values established for the early development phase. It is expected that these values will improve through development and consequently result in a higher reliability for production motors. Based on the proposed Development, PFRT-Qualification, and Research and Development flight test program, predicted and maximum demonstrable reliabilities for critical failures have been established. These data are presented in Table XVI.

Table XVII presents predicted reliability of stages produced by clustering NASA Booster motors. These reliabilities are based on the assumption that single motor reliabilities will increase after the early flight test program with continued static-testing and that the need for the larger clusters would correspond to the time schedules shown in the table.

*A critical defect is one that judgment and experience indicate could result in hazardous or unsafe conditions for individuals using the product or could prevent performance of its tactical function.

**A major defect is a defect, other than critical, that could materially reduce the usability of the unit of product for its intended purpose.

TABLE XVI

PREDICTED PERFORMANCE RELIABILITY OF A 3-SEGMENT MOTOR

Phase	I (R and D)	II (PFRT and Qual)	III (Flight Test)
Motors	4	6	30
Predicted reliability at 90 percent confidence level (end of phase)	88.7	90	98
Maximum demonstrable reliability at 90 percent confidence level	56.2	79.4	94.4

TABLE XVII

PREDICTED RELIABILITY OF CLUSTERED NASA BOOSTER MOTOR STAGE

Motors in Cluster	Segments in Each Motor	Years After Motor Flight Test Program Completed	Predicted Motor Reliability	Predicted Stage Reliability
3	3	½	98.0	94.1
4	5	1 ½	99.5	98.0
16	5	2 ½	99.75	98.3

J. Facilities and Processing Operations Plans

The facilities described in the detailed report represent a total manufacturing plant. Flow paths for inert and reactive materials have been laid out in a continuous fashion to provide efficient utilization of equipment and manpower on a full production basis. Facilities costs are required to determine a meaningful figure for dollars/pound of payload in comparison with other missile systems. In the event of activation of all or a portion of the proposed facility, detailed designs and modus operandi would be provided by an architectural and engineering firm to GCR specifications to assure adequate master planning, efficient and flexible operation, and growth potential. Portions of the cost estimates have been provided by AETRON and Ralph M. Parsons, Inc.

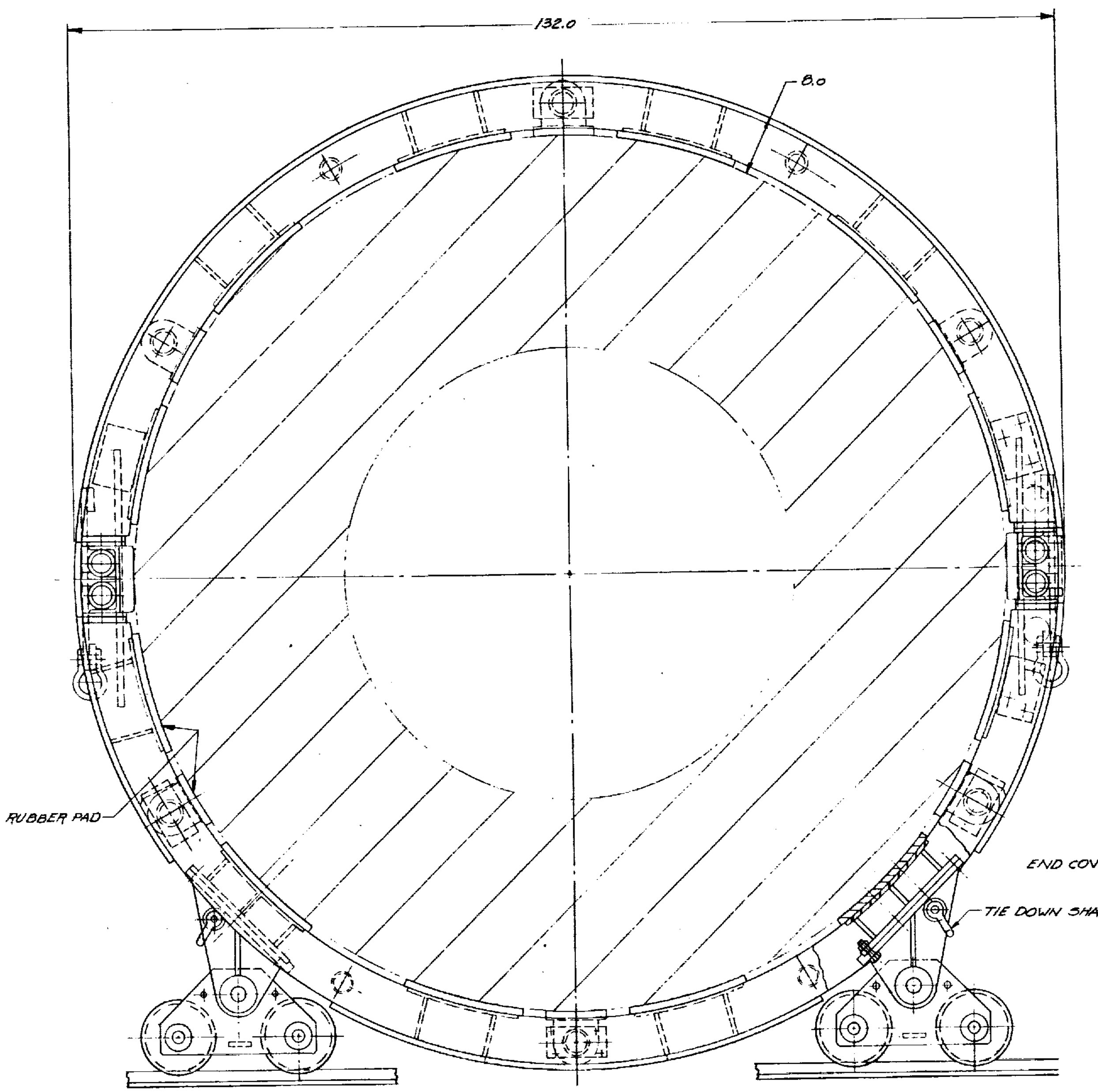
To provide continuity in this study, a propellant production rate of 750,000 pounds/month has been designed in accordance with the Phase III schedule. This rate requires one-half time utilization of two 300-gallon batch mixers. A brief discussion of a continuous mix propellant operation is given in the detailed report, but it is felt that, based on industry-wide record with continuous mix propellant, such an installation cannot be justified within this program. While advocates of high-rate continuous mix cite advantages in lower manpower requirements, propellant uniformity, and safety, none of these are clear cut as distinctly favoring continuous mixing over a batch operation. Continuous mixing loses flexibility in that it requires stockpiling motor cases to make its operation economical.

The cost estimates, processing plans, and manpower requirements envision an efficient "single purpose" manufacturing unit. Smaller motors would not be processed within the facility but would continue to be produced at GCR's Redlands site.

The motor parts will be shipped from the vendor in a handling harness (Figure 23) and this harness will remain with the motor segment throughout processing and testing operations. The harness will allow handling in either a vertical or horizontal position and will permit rotation from one attitude to the other. Wheels parallel to the longitudinal segment axis will mate with tracks throughout the processing buildings and with tracks on the in-plant transporter and test stands. The wheels are removable, however, and can be replaced with wheel sets, normal to the longitudinal motor axis for loading and off-loading from low-bed highway transporters and railroad cars.

The wheel sets have vertical and lateral adjustment features to aid in motor assembly for hydrotesting and static-firing. The handling harness rings are padded on the internal surfaces with rubber to permit chamber growth when pressurized. The harness rings will also provide some support opposing motor ovality during the processing and assembly operations although it is anticipated that additional fixturing will be required for this purpose.

The proposed transporter for in-plant use will be a towed two axle trailer as shown in Figures 24 and 25. It is designed to be towed at a maximum speed of 10 mph when carrying a motor segment. Large diameter, low pressure tires provide a suspension system.



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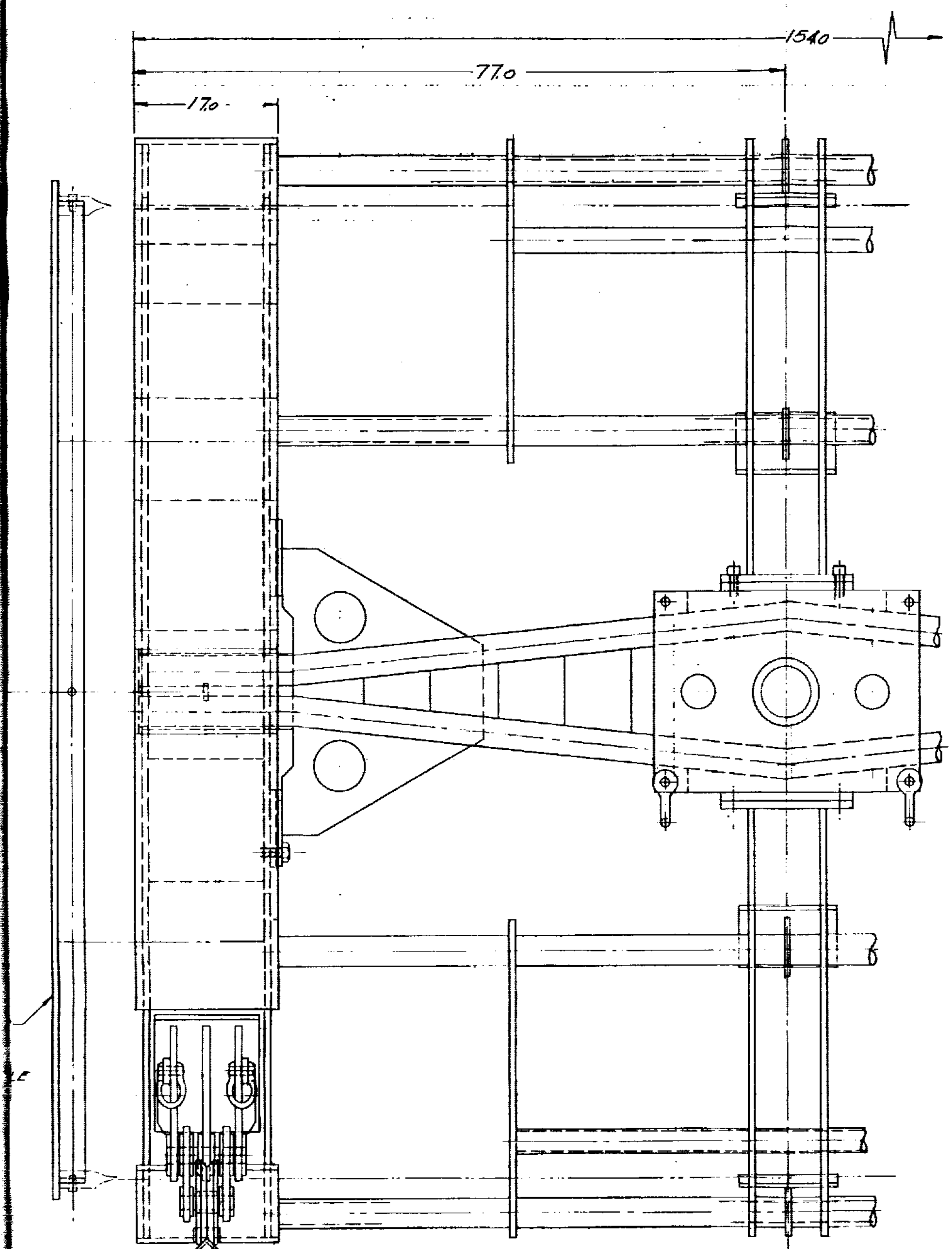

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Figure 23 Booster Segment Handling Harness

Figure 24 NASA Booster Segment Loaded on Trailer

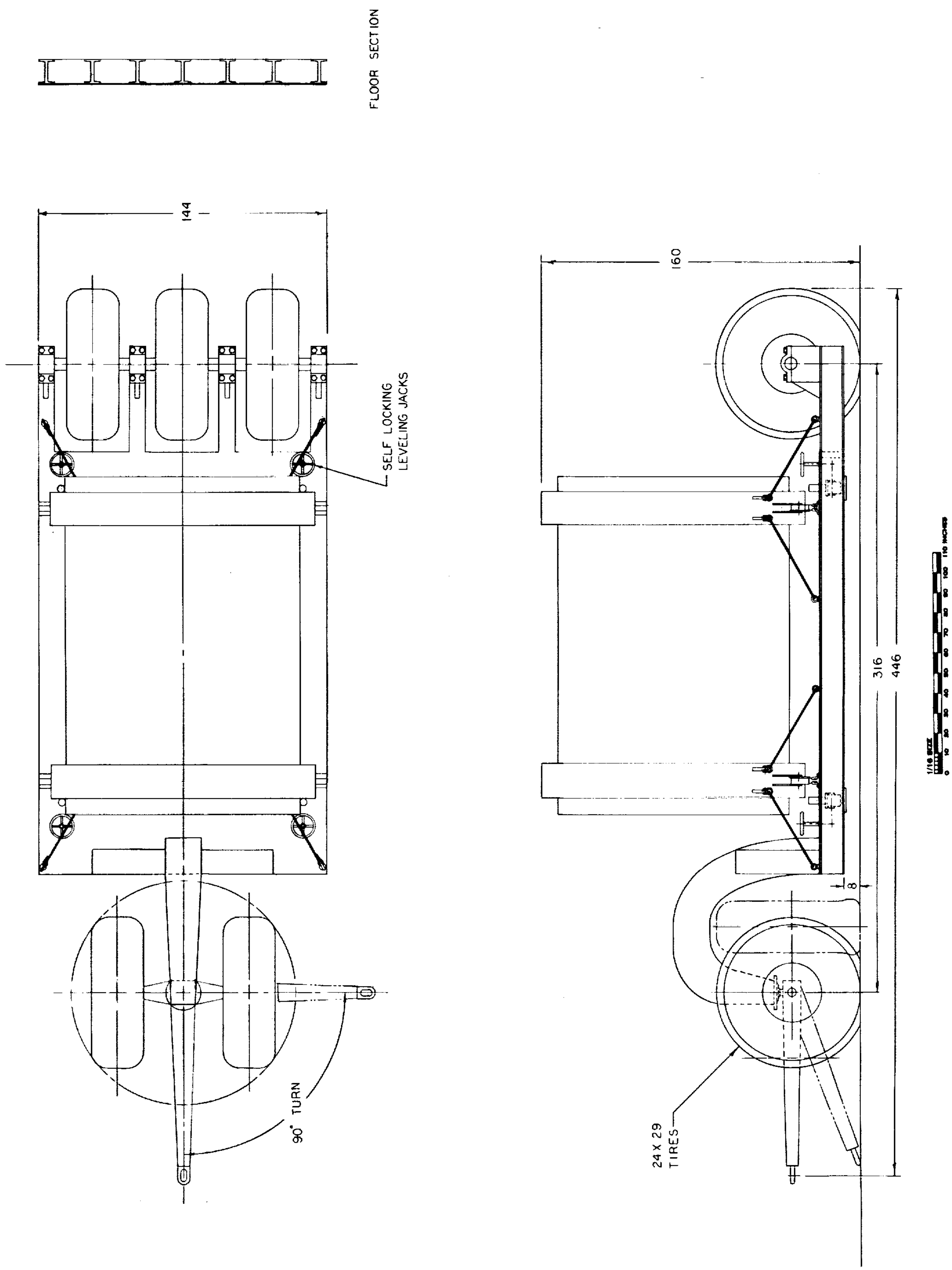

Figure 25 Details of NASA Booster Segment Trailer

Over-all width of the unit will be twelve feet with a length of 37 feet from towing eye to rear of the vehicle. The height can be varied in accordance with the required ground clearance. It has been shown in the figures with an over-all loaded height of 13 ft 4 in. and a ground clearance of 8 inches.

The trailer structure will be of welded steel structural shapes and plates. Tracks for rolling the segment, with its handling harness, onto the trailer are positioned crosswise to the bed. Phase I trailers will have railroad rails for matching in-plant tracks while Phase III trailers will have "V" tracks to match those on the highway transporter or rail cars. Jacks located at the four corners of the trailer bed will provide for 6 inches of vertical adjustment for aligning tracks and for steadying when loading and unloading.

The training phase will start sixty days before the facility start-up date and will consist of personnel training, equipment, tooling, and facility check out, procedure writing, and revisions to equipment, tools and facilities as required.

During this phase mild steel full-scale motor sections will be put through all the processes required to produce and test the live unit. Mixing of inert propellant will be part of the facility check out.

K. Quality Assurance

The nature of the process associated with the fabrication of the NASA Booster motor segments necessitates a rigid, before-the-fact quality control program aimed at early detection of defective materials and processes. This is essential to the program from the standpoint of both cost and reliability.

With this in mind emphasis will be placed on incoming materials inspection and in-process inspection as a means of achieving this goal. Specifications, which spell out those tests that truly affect the quality and performance of the product, will be given special attention. Check and rechecks (redundant inspection) will be used in various critical process areas. Surveillance type inspection (over the shoulder) will be used to supplement laboratory testing.

Training programs specifically aimed at indoctrinating personnel into the large booster concept will be instituted at the very beginning of the development program and maintained through the development program so that, when production begins, there will be no costly delays and mistakes while such training is performed. The primary training of the quality control engineers and inspectors will be accomplished by having them work alongside the development engineers. Secondary training will be provided in the form of specialized training in processing, manufacturing, metal parts inspection, statistical quality control, etc.

Quality control procedures and inspection will be concentrated in four areas:

(1) Chemical, physical and ballistic laboratory testing of raw materials, in-process materials and products.

(2) Hardware, tooling, and materials.

(3) In-process inspection (on the line).

(4) Ballistics testing, assembly, and motor handling.

The details of these controls and inspections are presented in the detailed technical report. Figure 26 is a diagram showing principal points of inspection and the over-all quality control plan.

L. Testing

In the design of the testing arrangement, as in other areas of the NASA Booster study, low cost is a design criteria. Flexured six-component test stands were rejected in favor of simple, heavyweight, truss-beamed structures capable of providing adequate tie down and of meeting minimum data accuracy requirements. Very large size is only the projection of basic principles proven to be reliable through GCR experience. In addition, however, motor assembly in the field constituted a major test consideration and was provided for in the stand design.

In order to evaluate all basic factors in considering horizontal versus vertical testing, conceptual layout sketches were made of each method. These sketches are shown in Figures 27, 28, and 29. Table XVIII provides a list of advantages attributable to horizontal and vertical test attitudes, but these may be summarized as follows: Since both horizontal and vertical test attitudes have been shown to be feasible, the selection is essentially resolved by considerations of safety, cost of the installation, flexibility of the installation, and motor set-up time. In all four areas, horizontal testing proves more advantageous.

To demonstrate performance of jet vane attitude control, the horizontal test stand is designed for three degrees of freedom and will be instrumented accordingly to measure three components of force: axial, lateral, and roll. The motor segment harnesses are equipped with wheel assemblies and are rolled onto the test stand rails. The wheel assemblies permit both vertical and lateral adjustments for positioning and alignment during motor assembly. Twelve tie-down locations per harness are provided for anti-flight restraint. The test stand, in turn, is fully supported from beneath with three mono-rail ball joint assemblies, one forward between the rails and one under the rear end of each rail. Only the two rear supports are active load measuring cells to measure motor side thrust

CHAMBERS INSPECTED

a. Vendor certifications reviewed
   1. Hydrotest
   2. X-ray
   3. Heat treat process
b. Dimensional conformance
c. Insulator bond strength

CHAMBER LINED

a. Cure time and temperature
b. Liner thickness
c. Liner weight
d. Liner bond strength and hardness

LINER SCREENING PROCESS

LINER MIXING

a. Viscosity
b. Mix time and temperature
c. Homogeneity of mix

MATERIAL PROCESSING

a. Moisture content
b. Material temperature

LINER RAW MATERIALS INSPECTED

a. Conformance to specifications
b. Lot check batch
   1. Insulating properties
   2. Bond properties

PREPARATION-INSTALLATION OF CASTING TOOLING

a. Condition
b. Alignment
c. Assembly

CHAMBER LOADED

a. Casting variables (rate
b. Cure time and tempera
c. Propellant physical pro
d. Propellant burning rat
e. Subscale motor data

PROPELLANT SCREENING PROCESS

PROPELLANT MIXING

a. Mixing variables (time, temp, etc.)
b. Viscosity
c. Strand burning rate
d. Bond strength
e. Curability
f. Physical properties
g. Homogeneity

MATERIAL PROCESSING

a. Oxidizer particle size
b. Blend ground to unground oxidizer
c. Moisture content
d. Material temperature

PROPELLANT RAW MATERIALS INSPECTED

a. Conformance to specifications
b. Lot check batch
   1. Subscale motor
   2. Physical properties

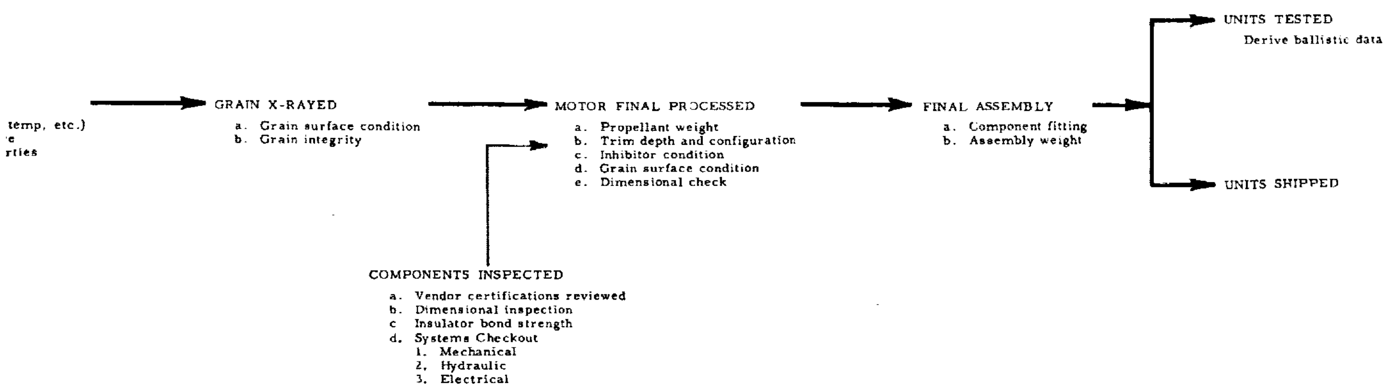

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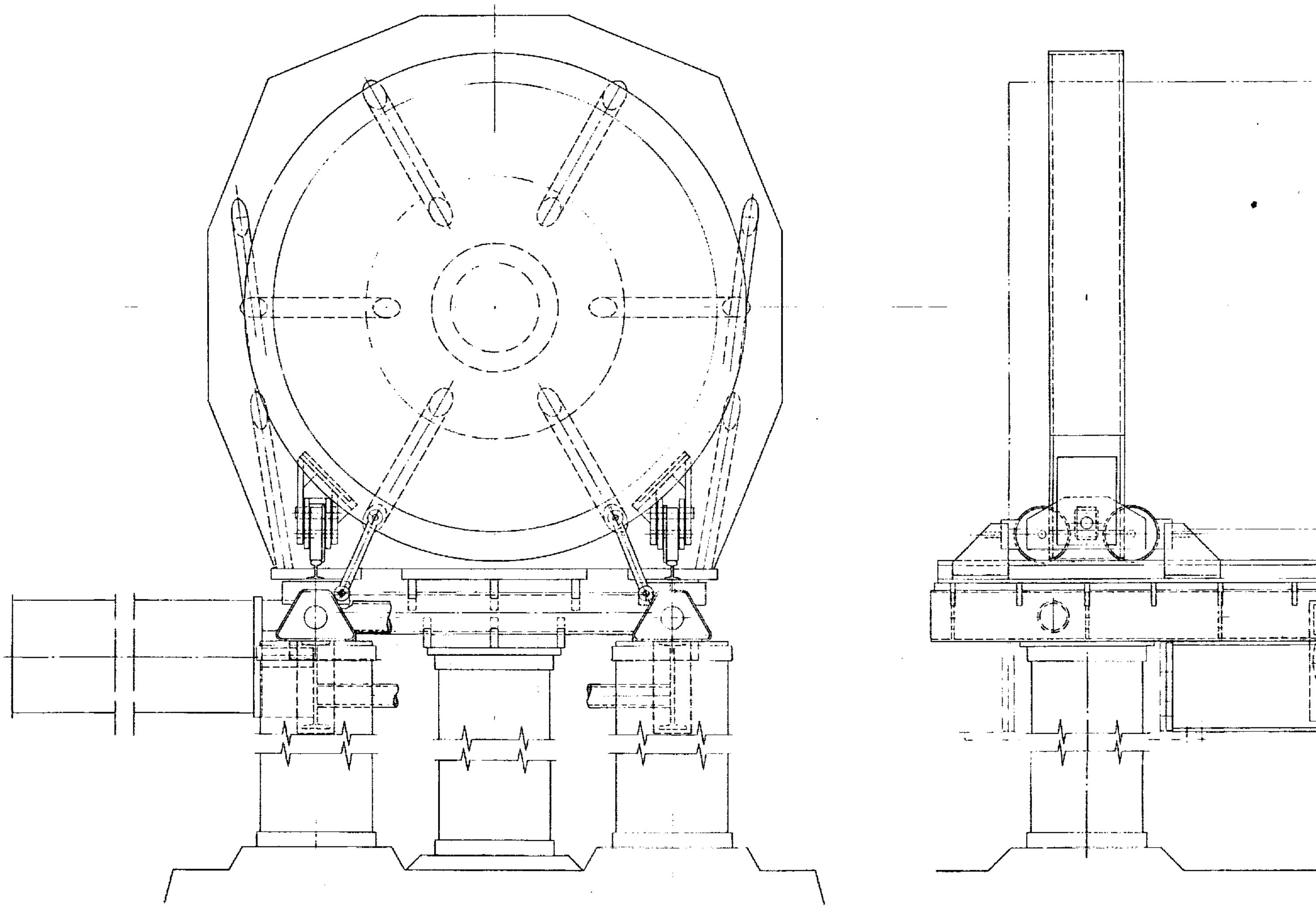
Figure 26 Principal Inspection Points, Booster Segment Processing

Figure 27 Horizontal Test of NASA Booster



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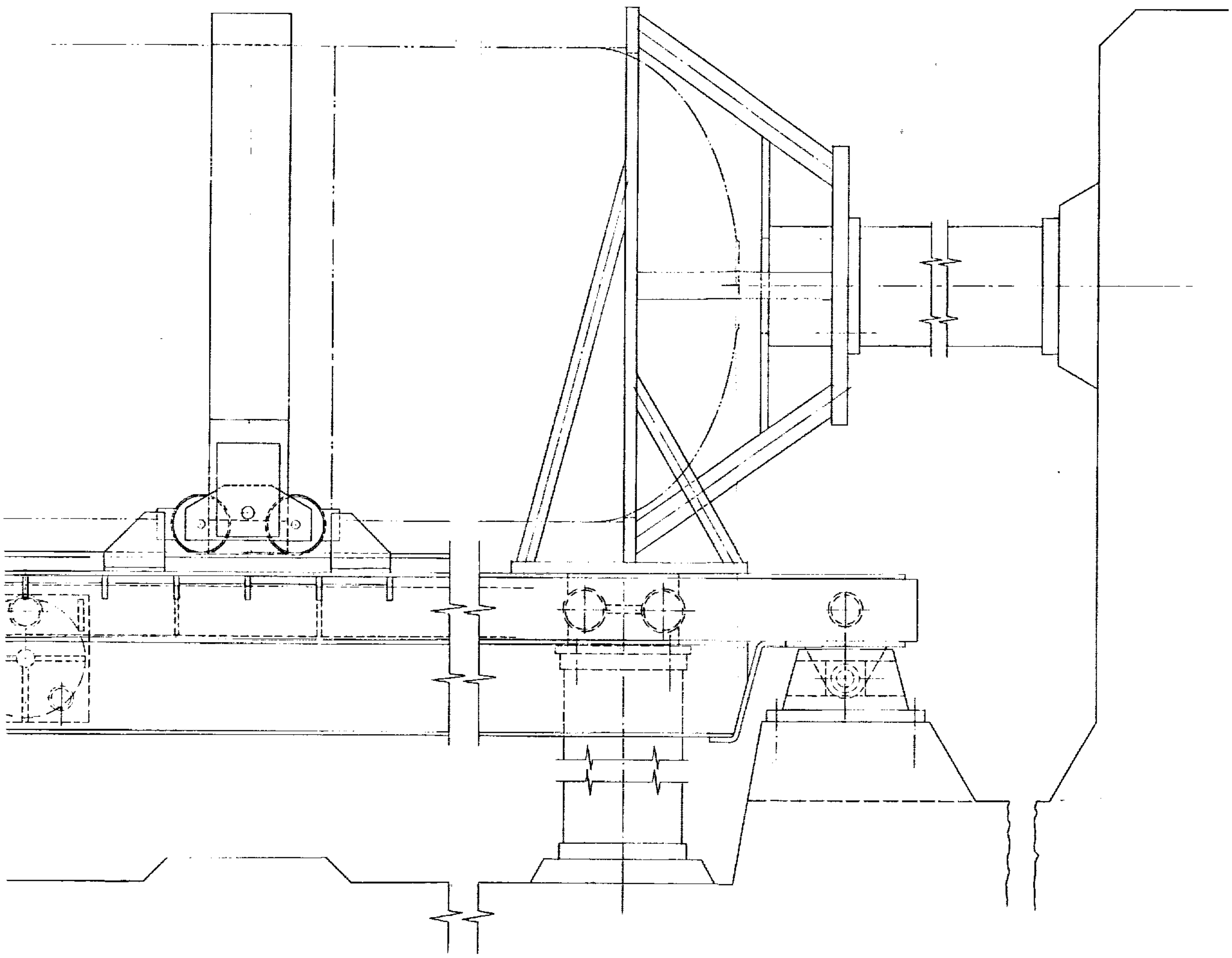


Figure 28 Details of Horizontal Test Stand

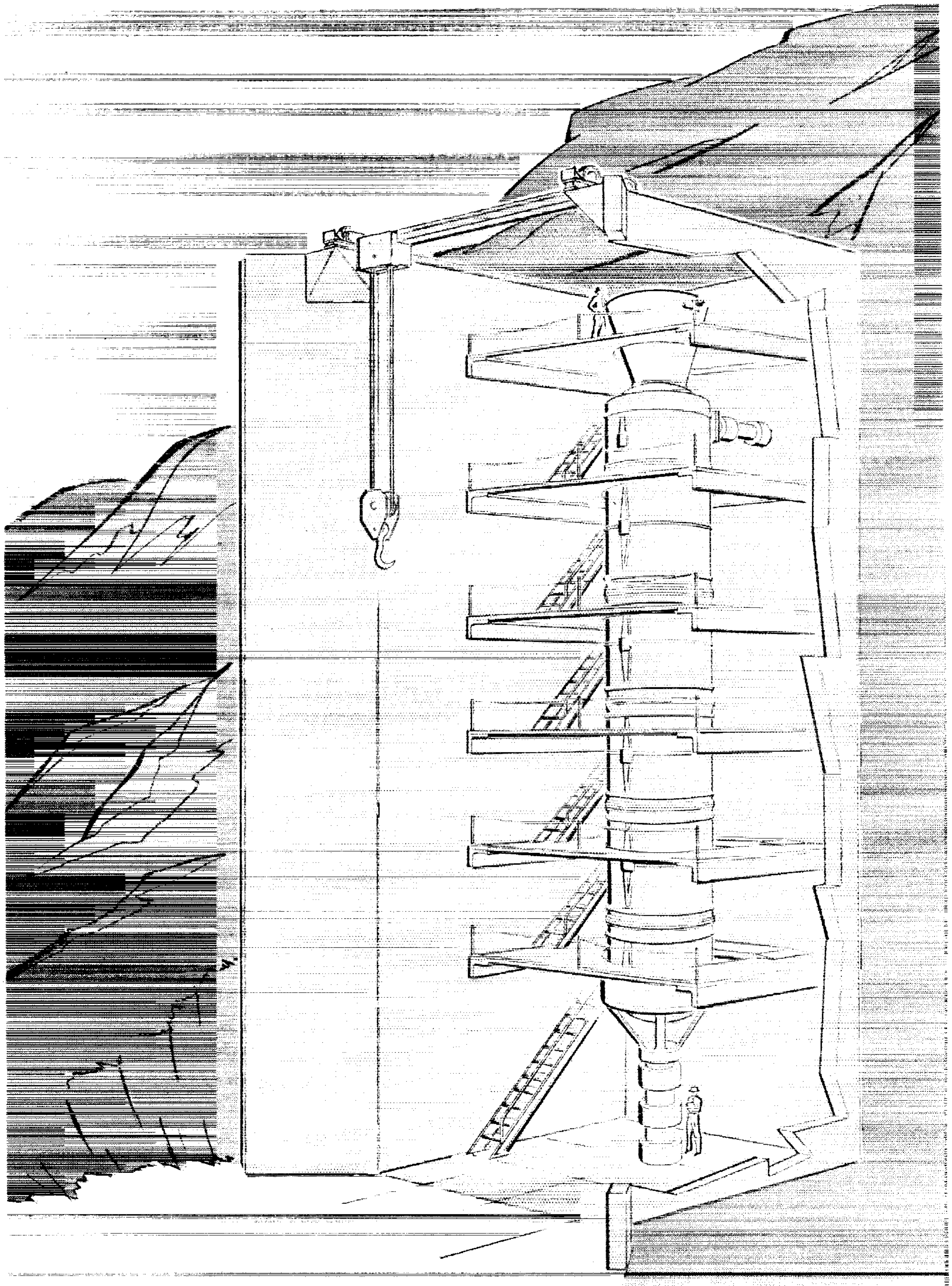


Figure 29 Vertical Static Test Stand for NASA Booster

TABLE XVIII

VERTICAL VERSUS HORIZONTAL STATIC TESTING OF NASA BOOSTER

Advantages of Vertical Testing

... Provides more accurate side thrust measurements by eliminating motor weight from force readings.

Δ Makes motor assembly easier by minimizing non-concentricity and slump in the segments.

... Permits better dispersal of toxic gases.

Δ Resembles flight situation more closely with respect to gravitational grain stresses and motor assembly techniques.

Advantages of Horizontal Testing

... Provides more accurate measurement of axial thrust by eliminating motor weight from force readings.

... Minimizes equipment costs and complexity for motor assembly and installation; vertical testing requires hoisting facilities and extensive scaffolding.

Δ Minimizes personnel hazards with respect both to working on elevated platforms and to escaping from impending danger.

Δ Accommodates different length motors more easily.

... Makes motor instrumentation easier.

... Assures higher data acquisition reliability through better transducer and cabling protection.

... Accommodates photographic documentation during a test-firing.

Δ Enables easier repair of damage to test bay due to motor failure.

... Reduces over-all cost of test complex.

... Requires less set-up time due principally to time of installing and removing scaffolding twice for each vertical test.

... Makes it easier to provide motor conditioning facilities.

Δ Provides anti-flight restraint more easily.

Δ Principal Factors

additively and roll forces differentially. It is possible to segregate motor loss-in-weight and center-of-gravity shift from the jet vane force measurements with sufficient accuracy to meet the established requirements. Horizontal support and movement are accommodated by two side ball joint assemblies, one forward and one aft. Axial thrust is transmitted through one multi-bridge load cell-ball joint assembly located at the head of the motor in line with the thrust axis.

Test-firing motors of the NASA Booster size and complexity on a thrust stand such as has been proposed will involve certain unavoidable data inaccuracies. An approximation of motor weight to be segregated from thrust measurements has already been mentioned. Generally, the principal error will result from the inability to calibrate load cells with direct static loads. The cells must be calibrated by impressing the load cell bridges with known voltages to simulate a static load.

Test data are divided into four categories in GCR test firings: primary, back-up, transient and high-frequency, and support. Each category is allocated to a measuring system designed to best fulfill the particular requirements, and all are fully described in the detailed technical report.

M. Transportation

The transportation survey was accomplished principally through study of previously published data and assistance from various agencies. The effort was materially aided by Mr. Louis Molinari of the Western Traffic Region of the Military Traffic Management Agency (MTMA).

Four general route studies were conducted to determine the feasibility and approximate cost of each method:

	From	To	Mode
Method A	Beaumont	San Pedro/Long Beach	Highway or rail
	San Pedro/Long Beach	Norfolk or Jacksonville	Ship or barge
	Norfolk or Jacksonville	AMR	Barge or rail
Method B	Beaumont	Cocoa Rockledge	Rail
	Cocoa Rockledge	AMR	Truck
Method C	Beaumont	AMR	Truck
Method D	Beaumont	Houston or Galveston	Truck or rail
	Houston or Galveston	AMR	Barge

Means of air transport were investigated briefly and ruled out as being impractical on a gross weight basis.

The investigation has shown all four general routes to be feasible although a wide disparity in prices exists, and different handling techniques are required.

The prices quoted for the transportation methods must be considered to be only order of magnitude in accuracy. Time did not permit a thorough analysis and recheck of the cost figures. For example, in some of the prices quoted, it is not certain whether they are on a free in-and-out (f.i.o.) or a berth terms basis, or whether crane services, inclement weather protection, tie-downs and dunnage, hold times, "dead-head" returns, and other factors are considered. In addition, many of the rates are subject to negotiation since AF GBL shipment is assumed to apply and no rate structure exists in the weight class under consideration. Also, state highway permit fees are often established on a trip-by-trip basis.

The study of the motor transportation considerations proved to be one of the most complex areas within the program scope. The feasibility of the various transport modes can be established, but certain factors affecting a choice among them cannot be resolved at this time:

(1) State highway authorities will not issue a ruling on a transportation request until an actual application for permit is filed.

(2) Certain of the shipping costs are highly quantity-rate sensitive. Generally, barge transport means are reasonable only if as many as 15 motor sections are shipped at once, and larger ships require 500 revenue short tons to make a port. Therefore, launch requirements control the cost feasibility of these means.

(3) Consideration must be given to whether booster delivery is limiting the missile buildup and if shipment time is a factor.

(4) Risk factors should be evaluated prior to shipment by inspecting equipment (such as barges) and determining failure incidence (such as storms at sea) from prospective shippers' records. Obviously, the risks of barge shipments during the hurricane season must be considered.

The weight and dimensional bases for the transportation study are as follows:

Forward head section	58,000 lb
Segment	110,000 lb
Aft head section	55,000 lb
Nozzle and TVC subsystem	10,000 lb
3-segment motor	343,000 lb
	(153 long tons, 172 short tons)

Length:	14 feet
Height:	12 feet
Width:	11 feet

The weights include allowances for the handling harness, blocks and bracing, tie-downs and end plates.

The plot of longitudinal acceleration shock spectra realized on a railroad freight car during humping shown in the detailed report indicates a level of 150 g's at 50 cps and above. The deleterious effect of repeated shocks such as these on the propellant cannot be analytically determined due to attenuation in the visco-elastic grain. It is proposed to subject sections of the environmental test motor to such treatment and to rough road tests prior to static firing. The results of these tests could influence selection of the transportation mode.

The cost details and selected routes of the four methods studies are shown in the detailed report. The totals per motor are summarized below:

Method A	\$49,400 (1 motor)	\$21,400 (3 motors) \$11,400 (6 motors)
Method B	\$25,700/3-segment motor	
Method C	\$29,000/3-segment motor	
Method D	\$39,200/(1 motor)	\$23,200 (3 motors)

As pointed out previously, these figures are approximate and must be considered as only general cost guides.

Port and crane services availability were surveyed, and state highway regulations, rail capacities, and water transportation means are thoroughly discussed. Preliminary design details of a highway transporter and pavement and bridge loadings are also shown. Figures 30 and 31 show sketches of the highway transporter. Table XIX shows the proposed highway route.

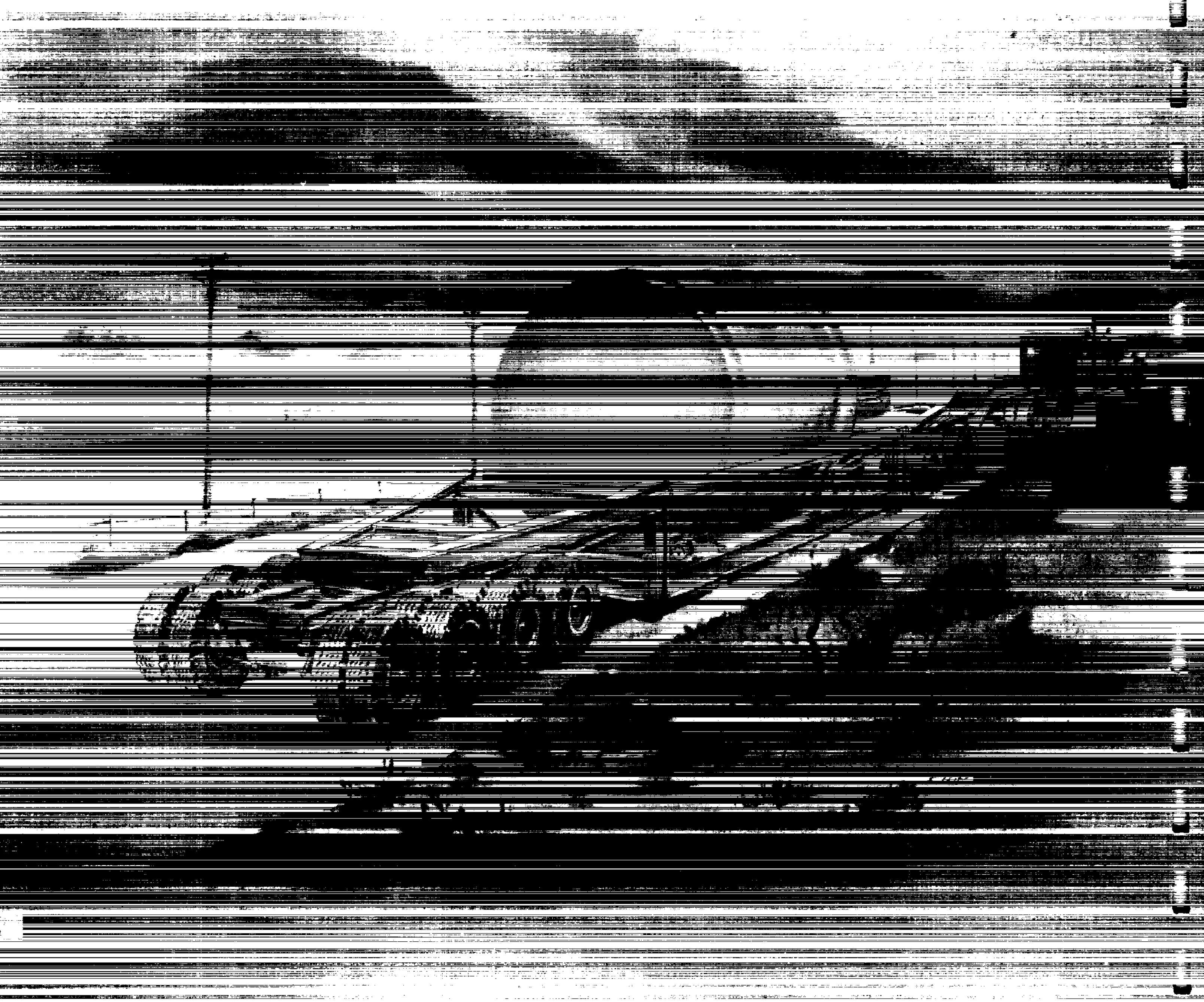


Figure 30 Highway Transporter, NASA Booster Segment

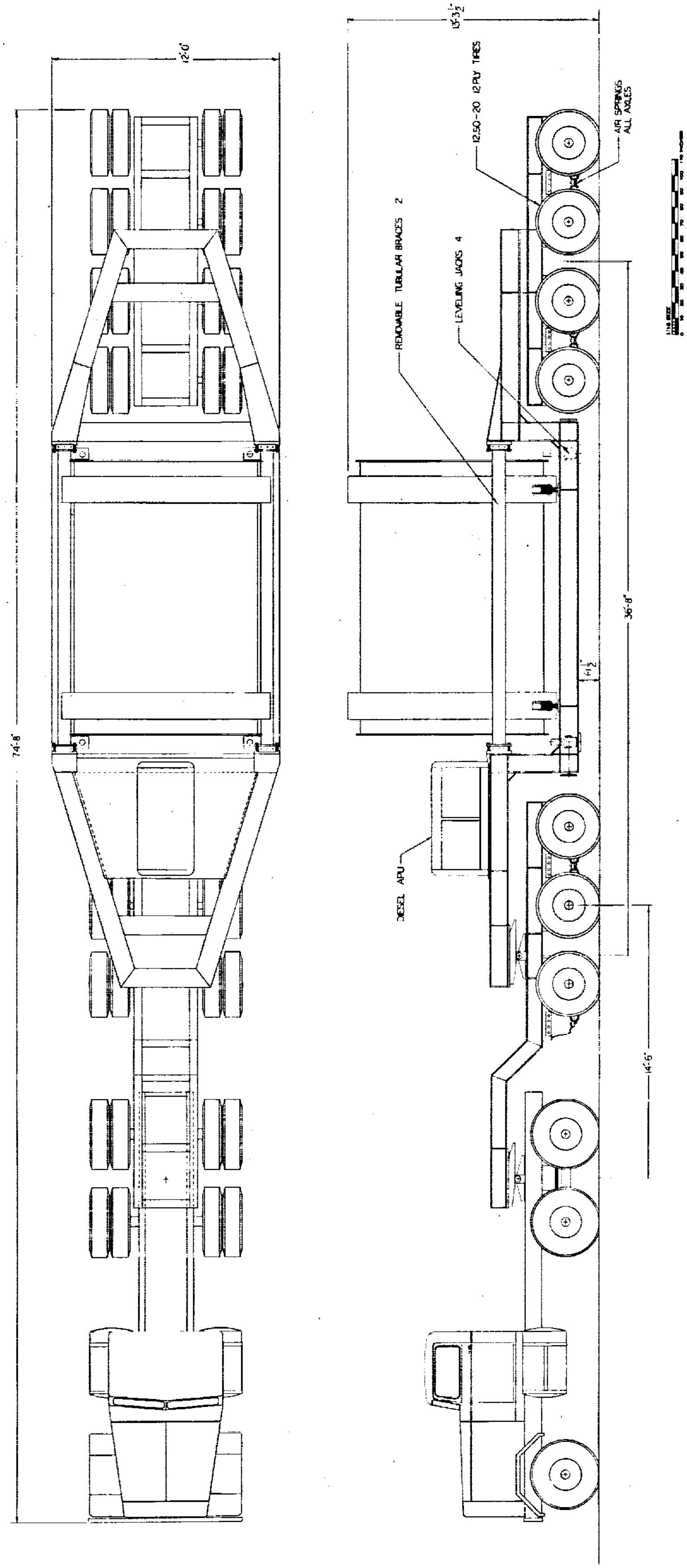


Figure 31 Details of Highway Transporter

TABLE XIX

PROPOSED HIGHWAY TRANSPORT ROUTE

Beaumont, California
to
Cape Canaveral, Florida

U.S. 99	to	El Centro, Calif.
U.S. 80	to	Gila Bend, Arizona
State 84	to	Tucson, Arizona
U.S. 80	to	Benson, Arizona
State 86	to	Lordsburg, New Mexico
U.S. 80	to	Kent, Texas
U.S. 290	to	Houston, Texas
U.S. 90 Bypass	to	Iowa, Louisiana
U.S. 165	to	Kinder, Louisiana
U.S. 190	to	Covington, Louisiana
State 21	to	Bogalusa, Louisiana
State 26	to	Poplarville, Louisiana
U.S. 11	to	Laurel, Mississippi
U.S. 84	to	Opp, Alabama
U.S. 331	to	DeFuniak Springs, Florida
U.S. 90	to	Tallahassee, Florida
U.S. 27	to	Claremont, Florida
State 50	to	Indian River City, Florida
U.S. 1	to	Titusville, Florida
County Road	to	Cape Canaveral, Florida

DETOURS

1. Pascagula, Mississippi - River Bridge
   Detoured via diversion through State Route 21, beginning at Covington, Louisiana via Hattisburg, Mississippi.

2. Bankhead Tunnel - Mobile Bay
   Via U.S. 84 rejoining U.S. 90 from U.S. 331 at DeFuniak Springs, Florida.

3. Cochrane Bridge - Mobile River
   Via same route as (2) above.

Note: Approximately 2550 highway miles.

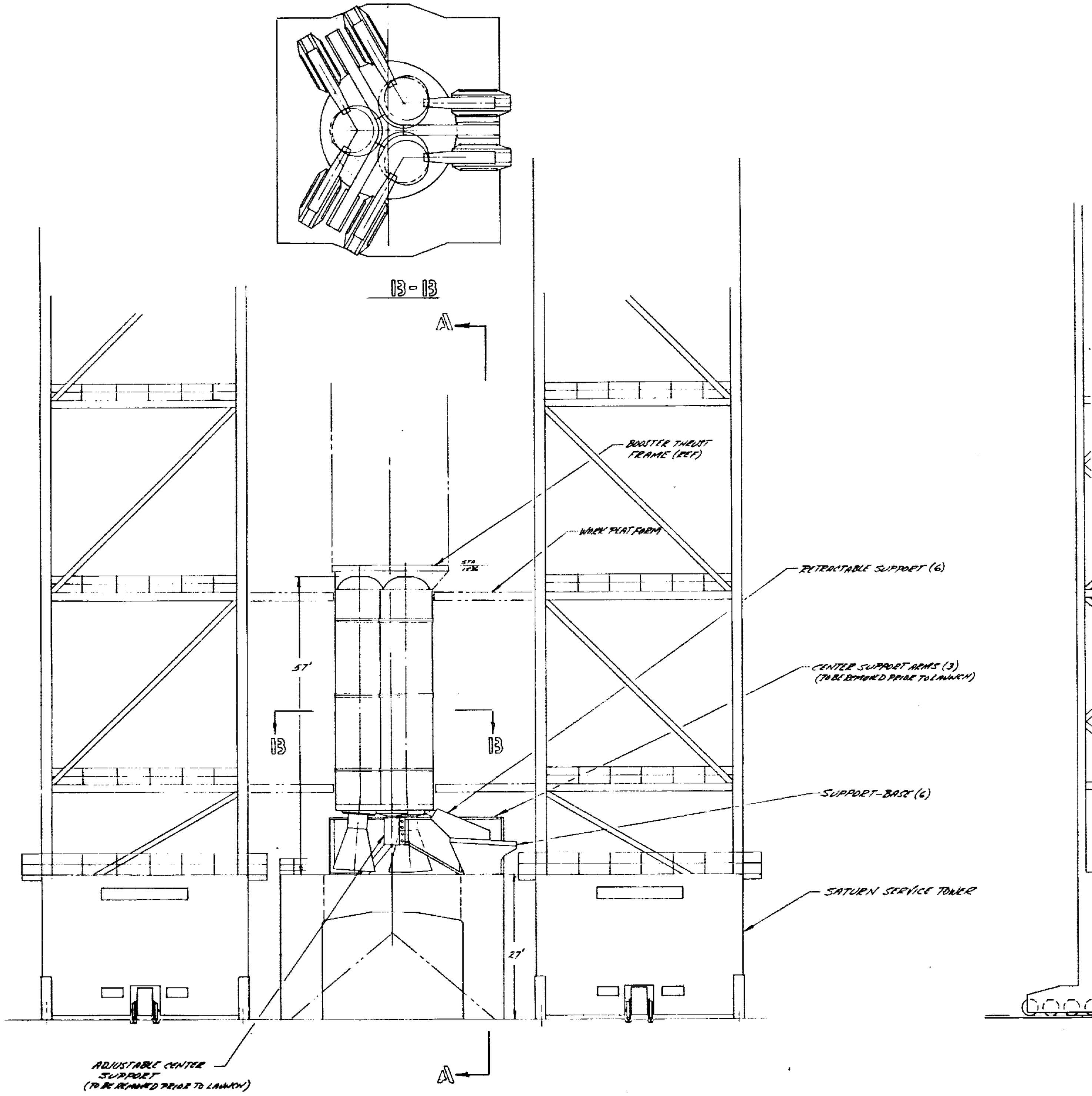
N. Launch Facilities and Operations

A brief study was made of the type of launch facilities which would be required and some of the assembly and operations methods to be used. The one million-pound gross weight vehicle, Vehicle No. 1, can be launched from a Saturn launch pad with only minor modification. The vehicle support structure would have to be constructed to support each of the three rocket motors in two places. Six retractable supports will be used in conjunction with an adjustable center support. The center support will be removed prior to launch as its purpose is to provide support during the assembly procedure. The vehicle would be supported on structural members built into the bottom of the rocket motors by use of extensions on the motor cases. The assembly of the vehicle would take place by assembling the bottom segments of three motors into a cluster. An assembly fixture would be attached to the top of the clustered segments to provide both a lifting attachment and a guide for placement on the pad. This assembly would then be lifted into place by the gantry bridge crane. The nozzles could be assembled either before or after placing the cluster bottom segments on the launch pad. The next step would be to place the upper segments in place one at a time until the entire first stage is completed with the interstage structure put in place last. At this point the upper stages could be assembled to the vehicle in the same manner as in the Saturn. The assembly work can be carried out with the present Saturn gantry and hoists. No significant changes are required in any of this equipment. The rocket motors are separated one foot at the closest point in order to facilitate the assembly of the segmenting joints.

The ten million-pound gross weight vehicle, Vehicle No. 2, will require a completely new launch complex. One concept that appears to have certain advantages is to excavate and build the pad partially below ground level. This arrangement reduces the required gantry height and allows for a convenient blast deflector design. A Saturn type tower would be utilized to handle all of the vehicle assembly, protection, and access. The tower would be equipped with a bridge crane and two hooks rated at 75 tons.

Drawings providing some details of the launch pads and assembly sequence are shown in Figures 32, 33, and 34.

In considering the cost effects of using solid propellant motors in the first stage, some study was also given to the launch complex. Briefly, it was determined that the costs of the launch complex and operations cannot be significantly reduced unless the liquid servicing requirements are completely eliminated. A percentage reduction in liquids used will reduce costs but only slightly. Very little additional ground support equipment will be required for the solid motors. This equipment would mainly consist of slings and assembly fixtures. Checkout and monitoring equipment for the solid propellant motors and their controls, ignition systems and hydraulics would be minor and involve only minor costs. The results of this phase of the study can be summarized by stating that launch complex differences are relatively small when compared with other system costs. An area where significant over-all cost savings might be achieved is in the reduction of launch preparation time. If this reduction can be accomplished an increase in launch rate can reduce launch operations costs to a significant degree.



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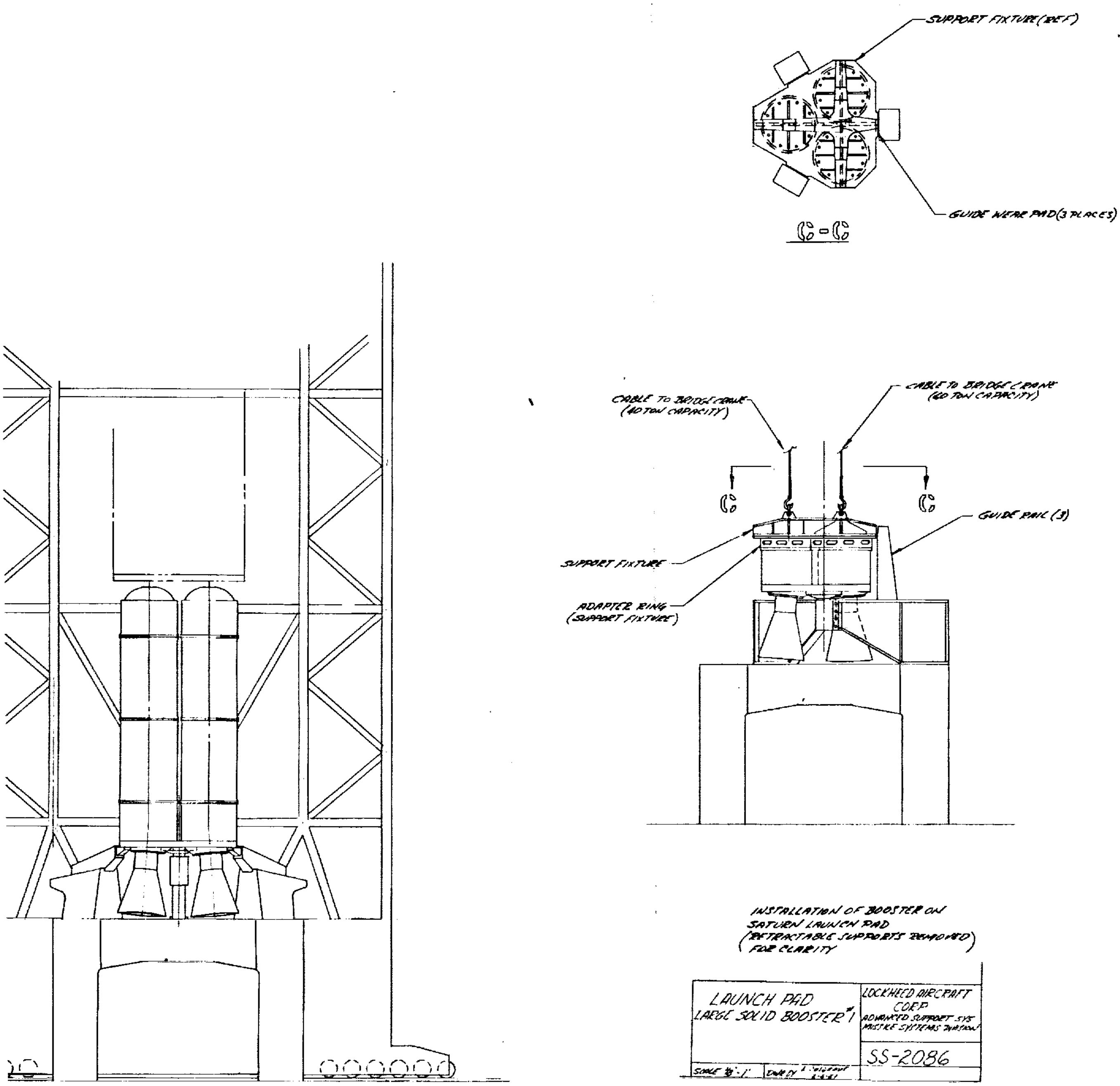

A-A

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Figure 32 Launch Assembly for Vehicle No. 1

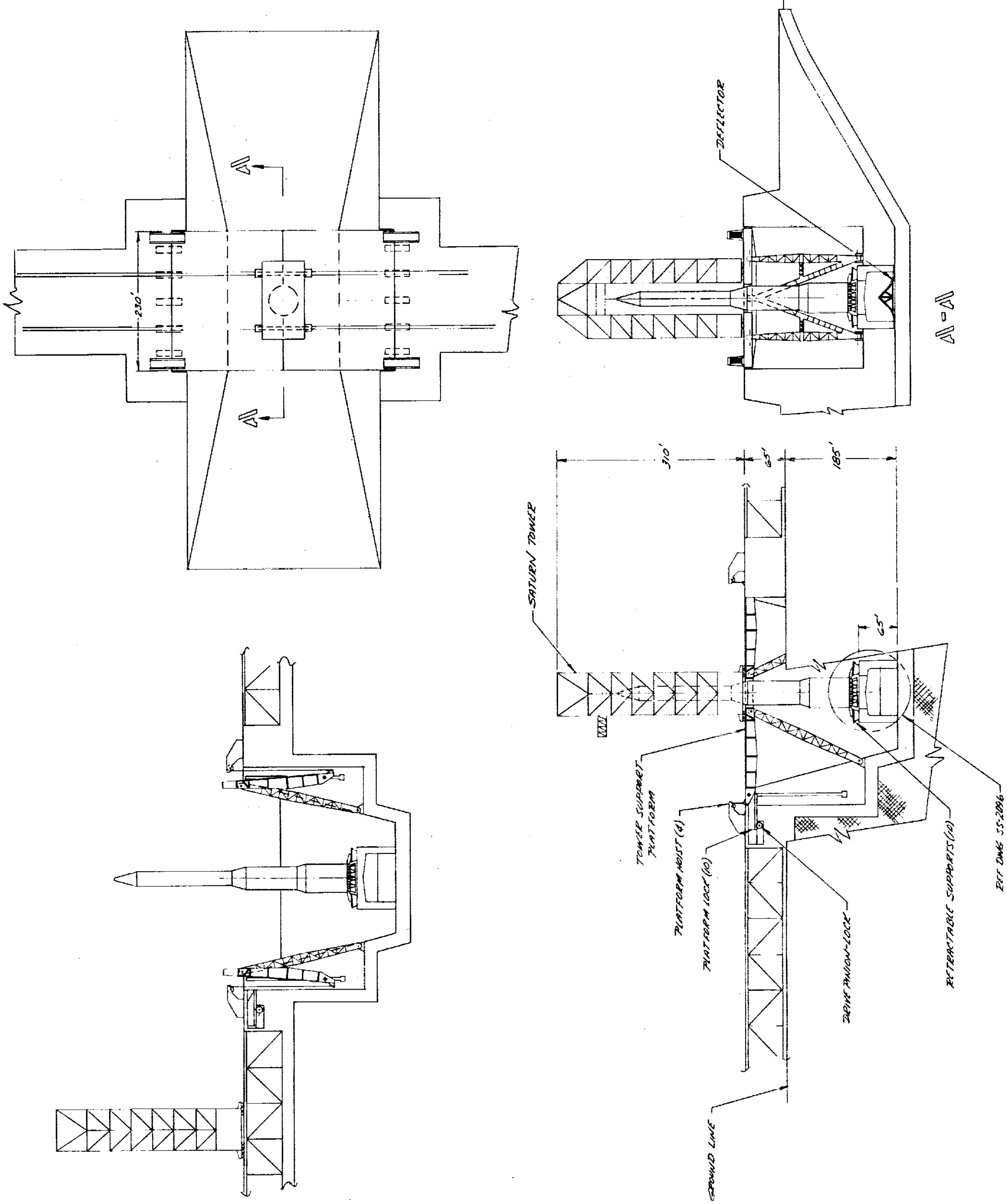
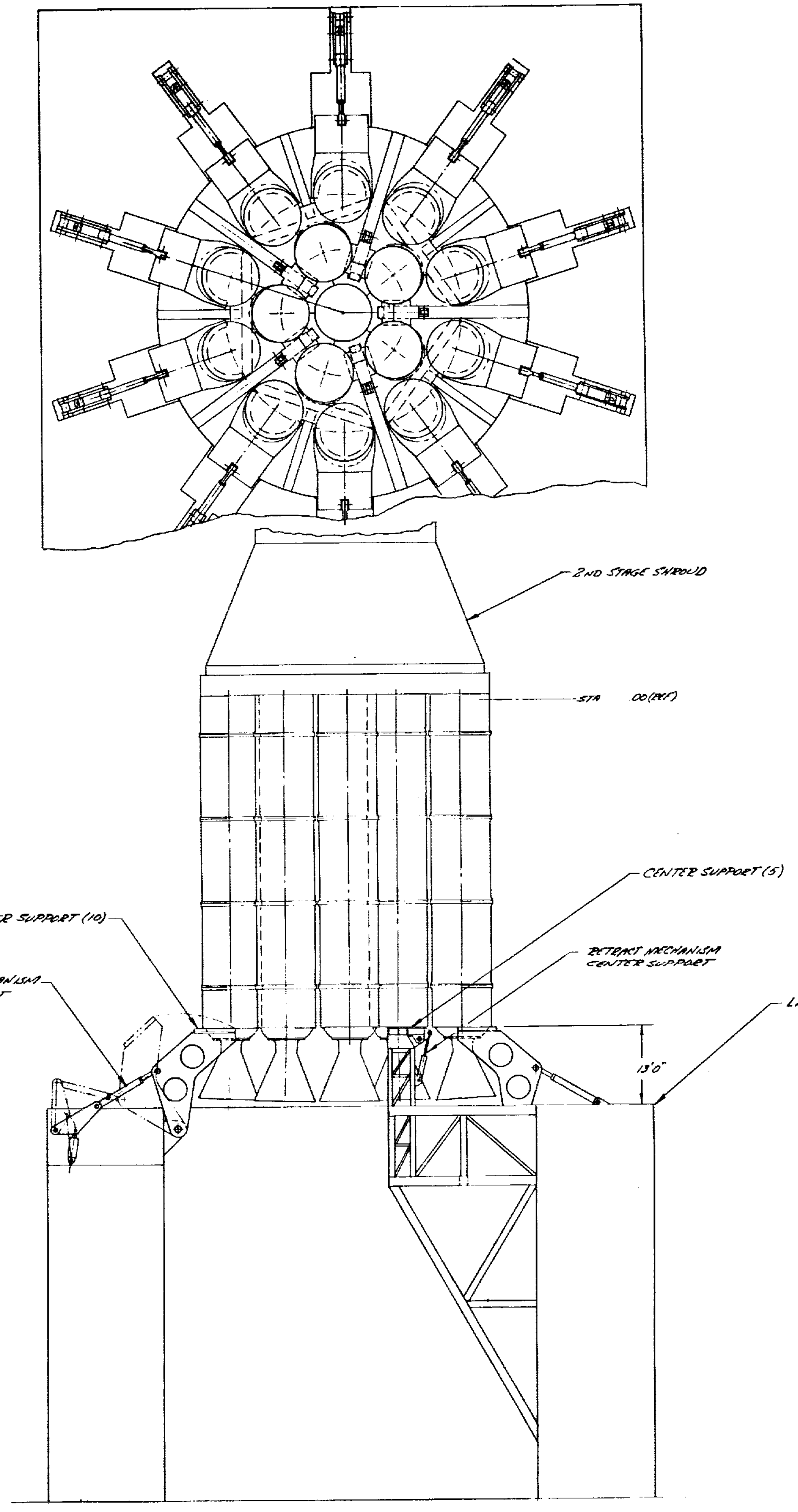


Figure 33 Launch Site for Vehicle No. 2



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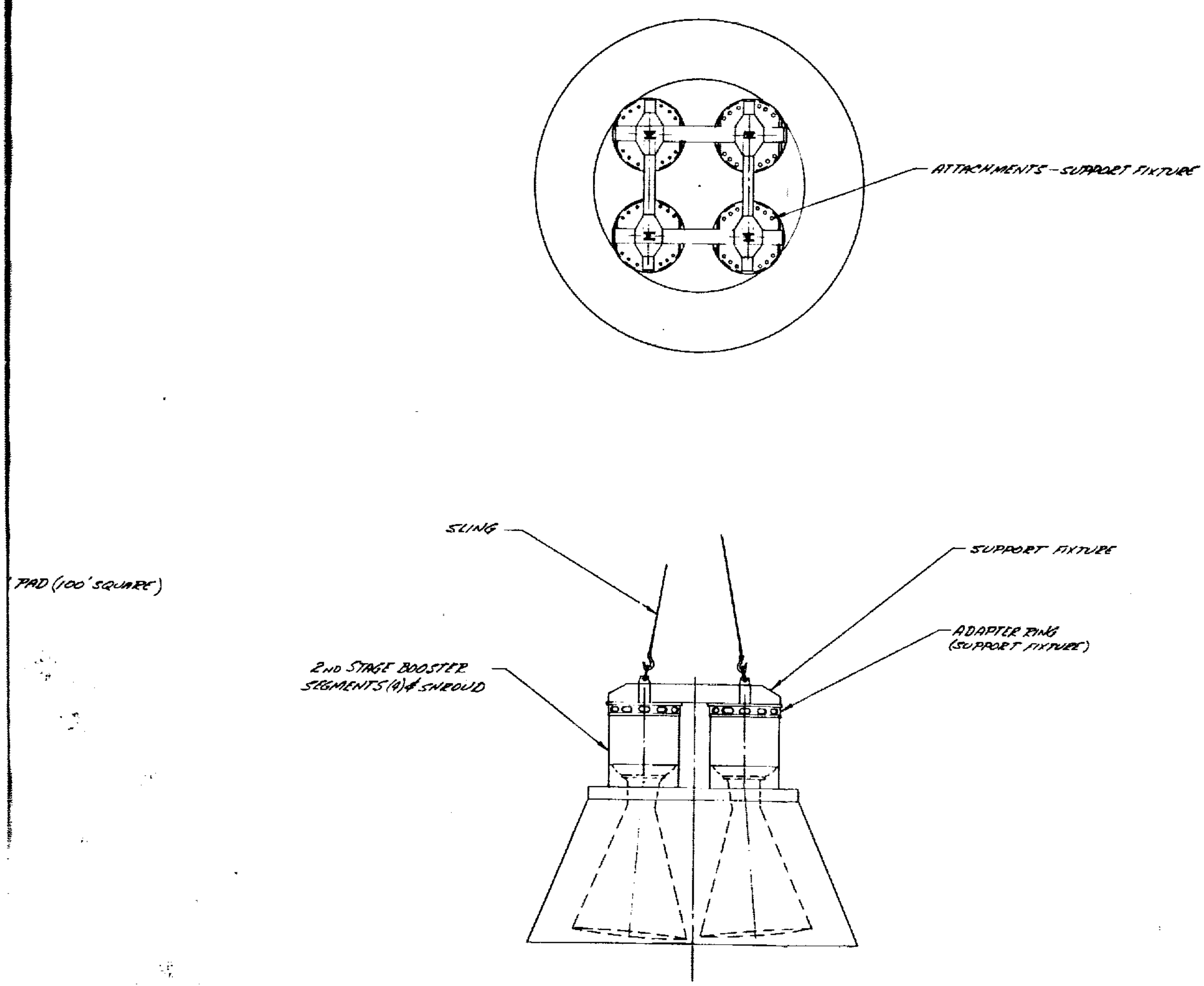
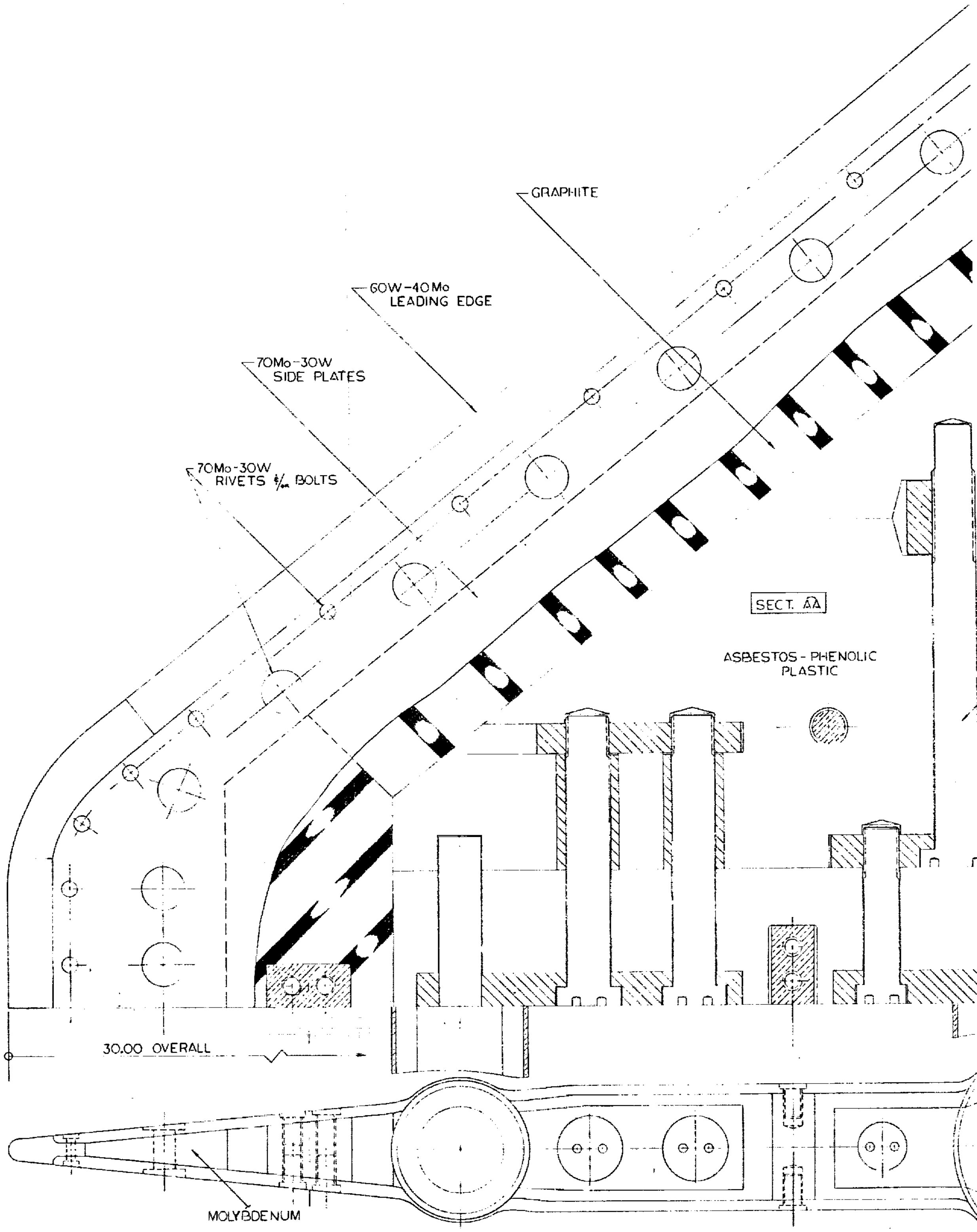


ASSEMBLY ARRANGEMENT OF 2ND STAGE
BOOSTER-LOWER END-FOR MATING TO 1ST STAGE
ESTIMATED WEIGHT - AS SHOWN 135 TON

FOLDOUT FRAME

Figure 34 Launch Pad Assembly for Vehicle No. 2

APPENDIX: DETAILED DRAWINGS OF JET VANES



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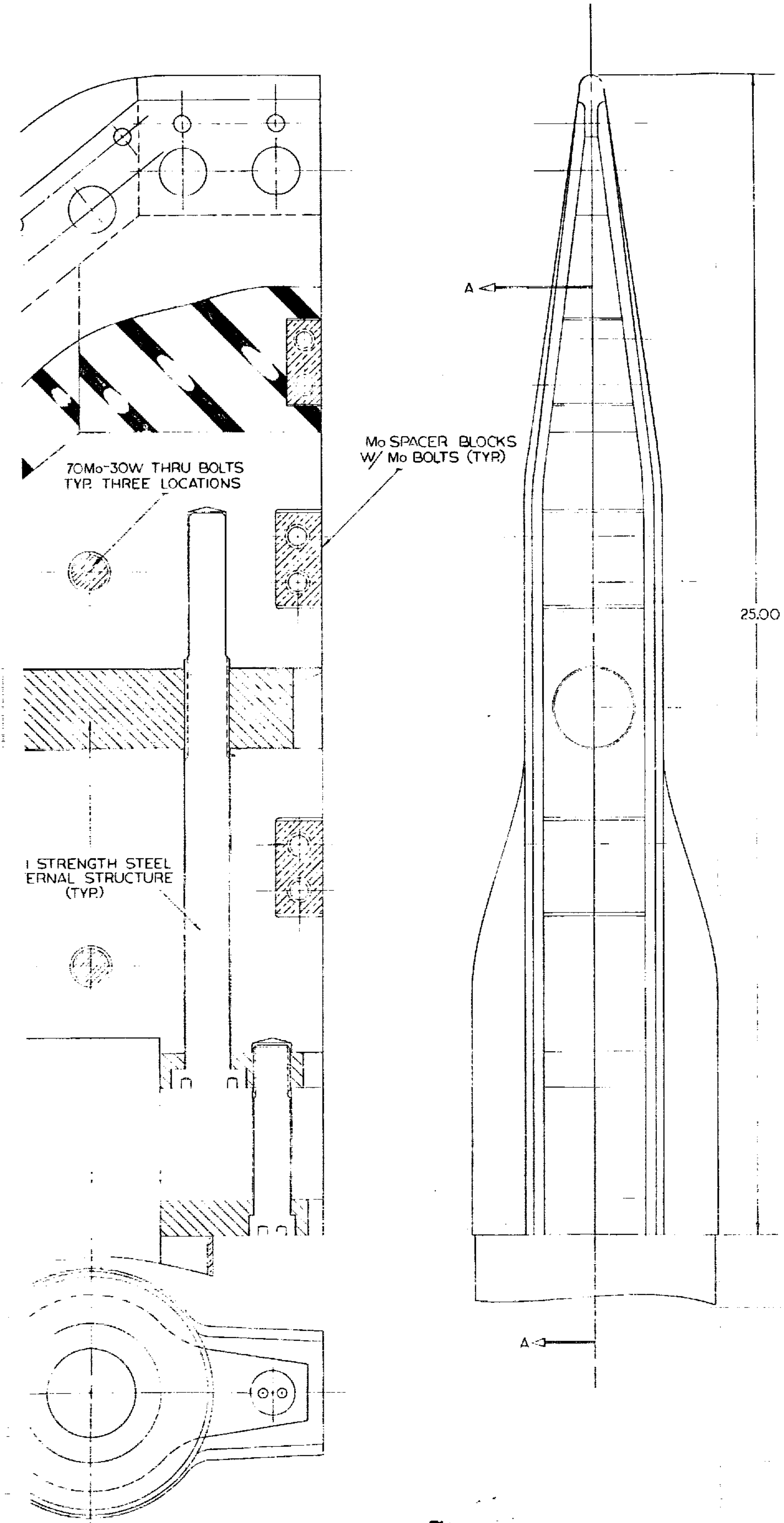

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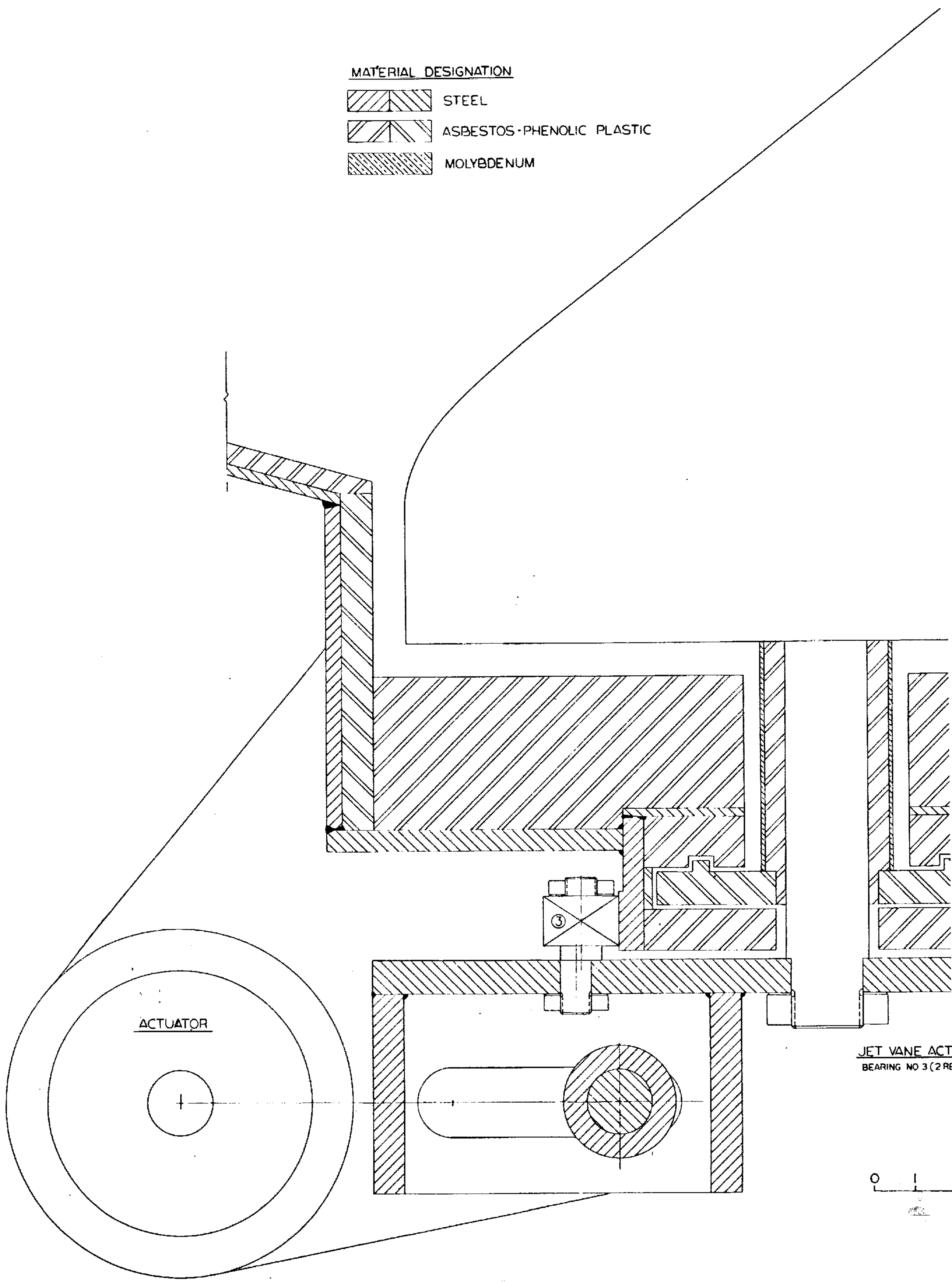
Figure A-1 Jet Vane Cross Section



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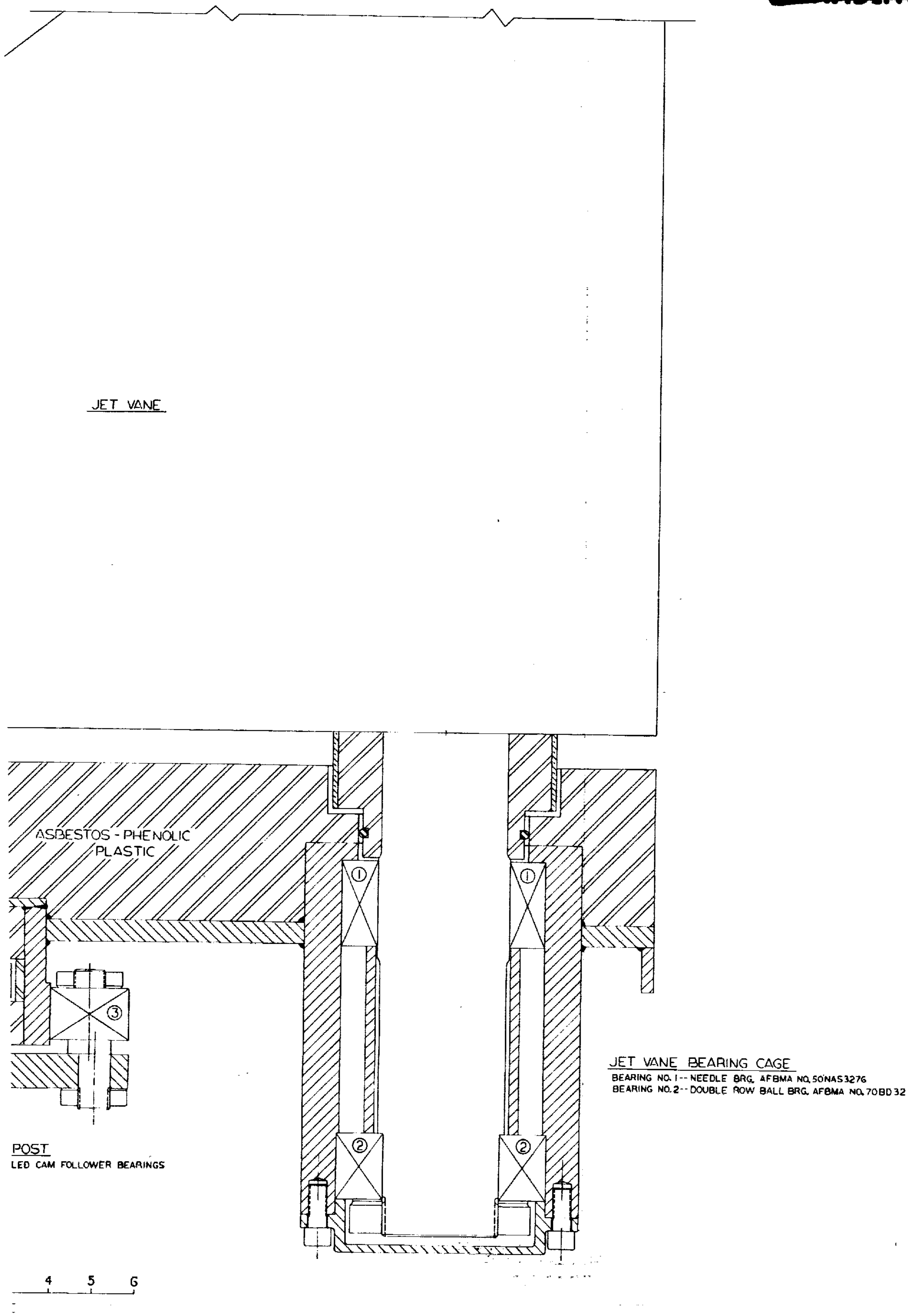

Figure A-2 Jet Vane Support Cages

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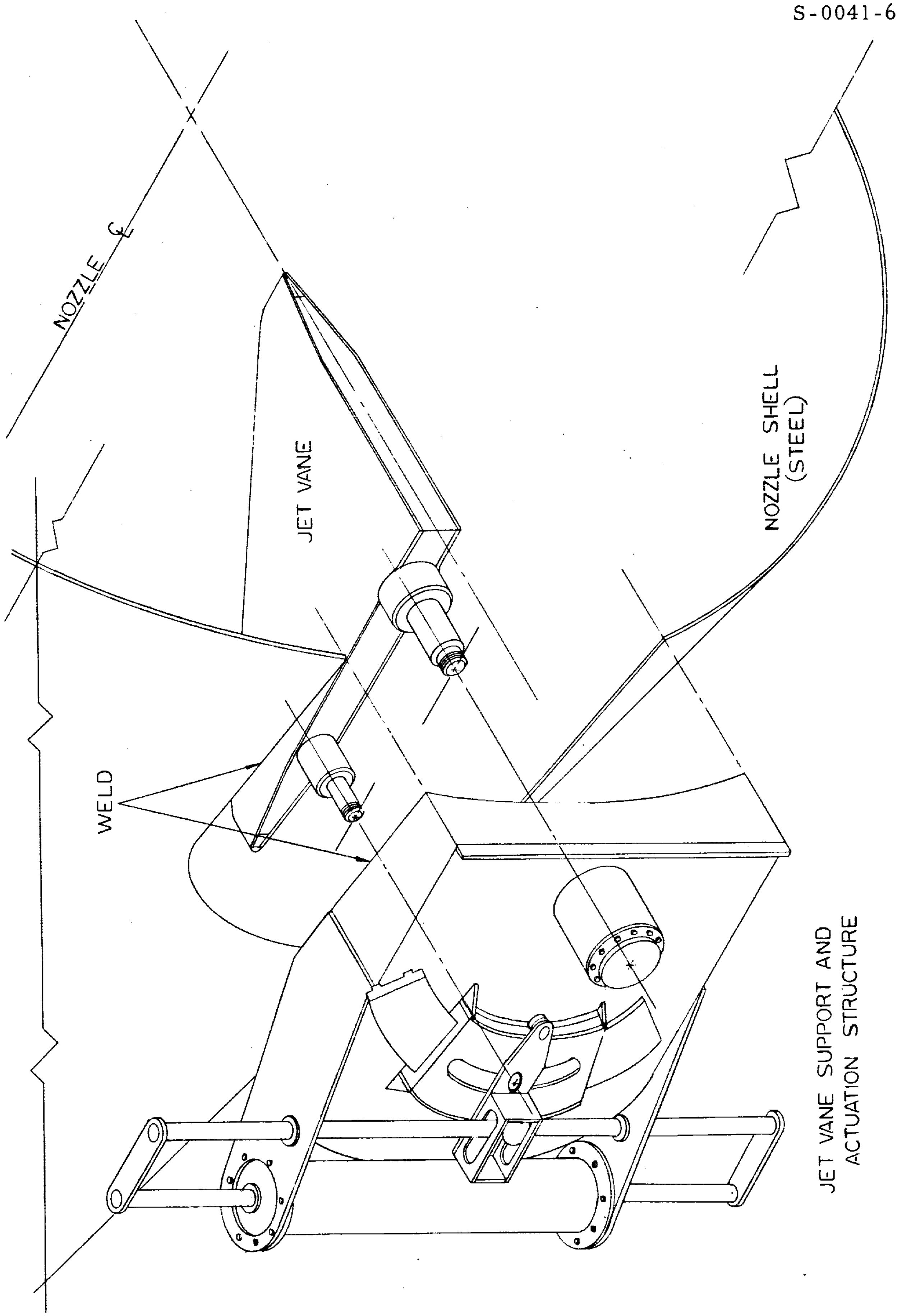

Figure A-3 Jet Vane Attachment to Steel Shell Nozzle

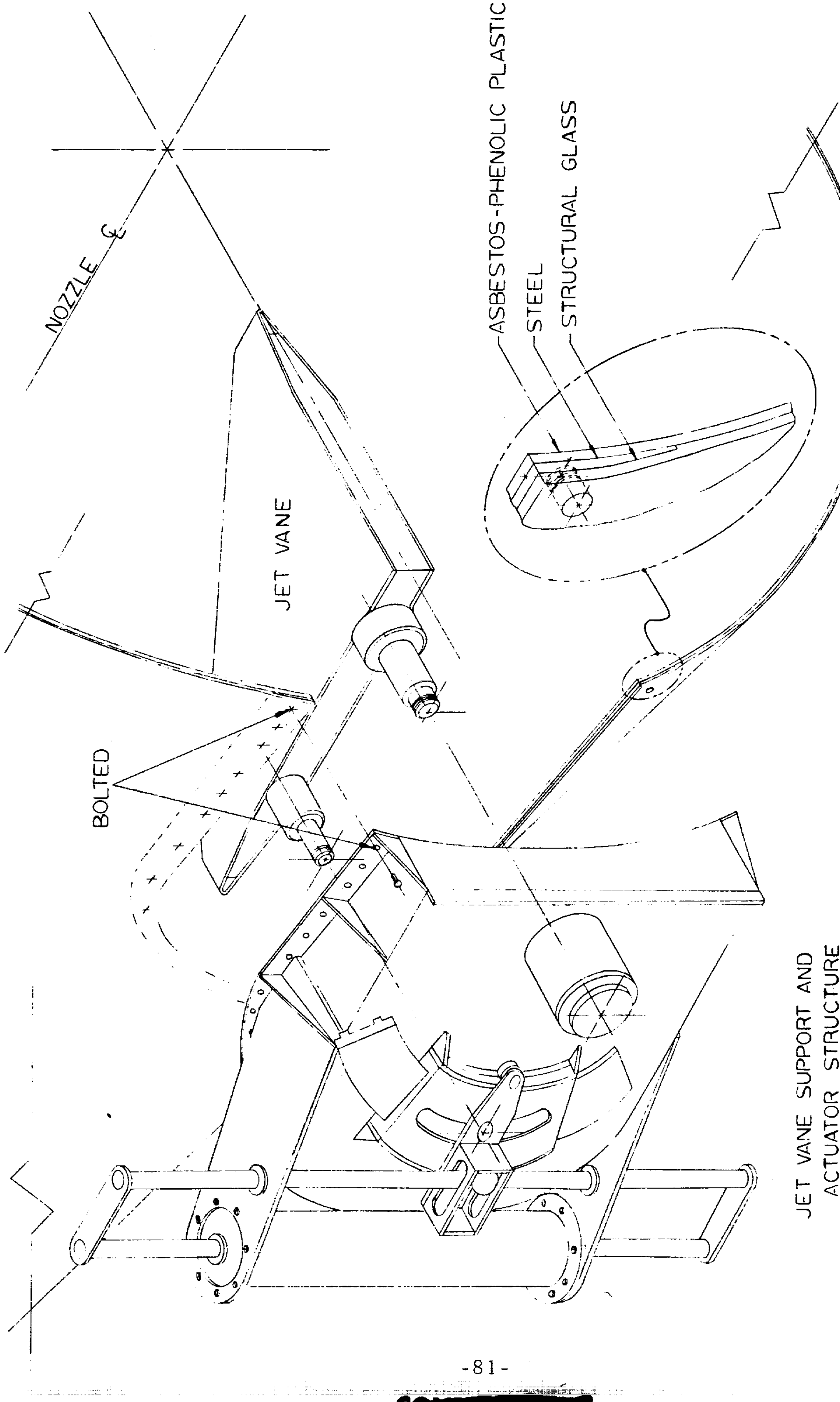

Figure A-4 Jet Vane Attachment to Glass-Wrap Shell Nozzle